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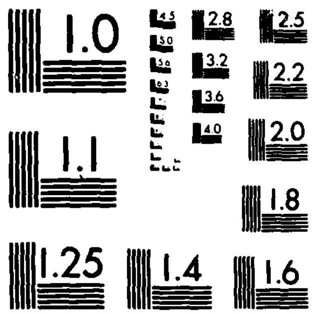


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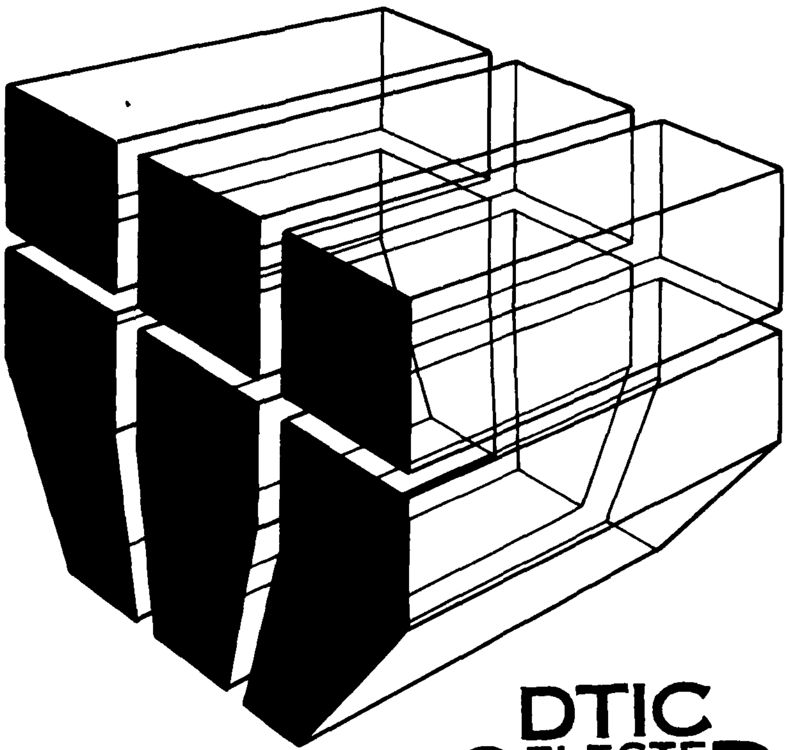
TECHNICAL REPORT N-173
January 1984



# LANDFILL GAS CONTROL AT MILITARY INSTALLATIONS

by
R. A. Shafer
A. Renta-Babb
J. T. Bandy
E. D. Smith
P. Malone







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This report provides information useful to Army personnel responsible for recognizing and solving potential problems from gas generated by landfills. Information is provided on recognizing and gauging the magnitude of landfill gas problems; selecting appropriate gas control strategies, procedures, and equipment; use of computer modeling to predict gas production and migration and the success of gas control devices; and safety considerations.

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## FOREWORD

This research was conducted for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE), by the Environmental Division (EN), U.S. Army Construction Engineering Research Laboratory (CERL). The work was performed under project 4A762720A896, "Environmental Quality Technology"; Task Area B, "Installation Environmental Management Strategy"; Work Unit 033, "Sanitary Landfill Leachate Control at Military Installations." The OCE Training Monitor was Mr. James Johnston, DAEN-ZCF-U.

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Dr. R. K. Jain is Chief of CERL-EN. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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# 1 INTRODUCTION

### Background

A traditional method of solid waste disposal is burial, more popularly referred to as landfilling. Natural processes occurring in the buried waste can transform the waste's constituents into leachate, a liquid effluent which may contaminate groundwater and surface water supplies.[1] These processes can also produce a gas effluent which can be an explosive hazard.

[1] W. J. Mikucki, et al., *Characteristics, Control and Treatment of Leachate at Military Installations,* Interim Report N-97/ADA097935 (U.S. Army Construction Engineering Research Laboratory [CERL], 1981).

Anaerobic decomposition of buried refuse produces relatively high concentrations of methane and carbon dioxide and smaller concentrations of ammonia, hydrogen sulphide, nitrogen, hydrogen, and carbon monoxide.[2] Under some conditions the presence of methane can create explosive hazards. The carbon dioxide is quite soluble in water, forming carbonic acid. The other gases are present only in trace amounts and cause more of a groundwater contamination problem than an explosive gas hazard.

Methane ($CH_4$), a colorless, odorless gas, is only slightly soluble in water and burns readily in air. It is generally very stable; but when mixed with air at a volume between about 5 to 15 percent, it is highly explosive.[3] Figure 1 shows the gas composition ranges

[2] T. W. Constable, G. J. Farquhar, and B. N. Clement, *Gas Migration Modeling,* University of Waterloo, Waterloo, Ontario.

[3] *Methane from Landfills: Hazards and Opportunities,* Symposium Proceedings, Denver, CO (March 21-23, 1979).

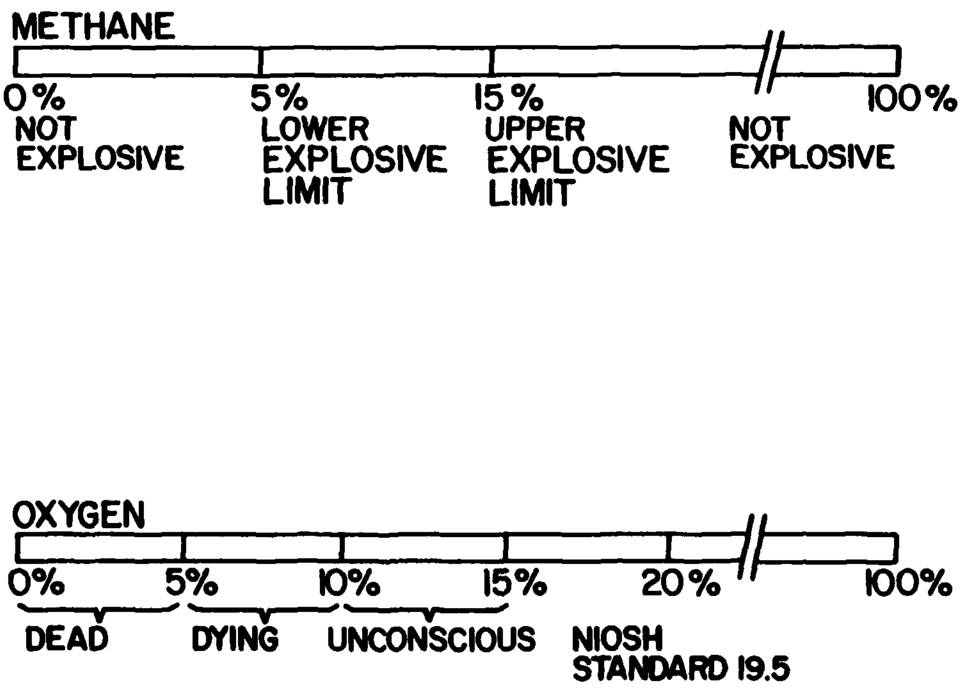


**Figure 1.** Danger of landfill gas. (From T. W. Constable, G. J. Farquhar, and B. N. Clement, *Gas Migration Modeling,* University of Waterloo, Waterloo, Ontario.)

related to combustion or explosion due to methane and suffocation from oxygen (air) displacement that can occur in structures and landfills. The amount of methane produced during the bacterial decomposition of organic materials exceeds the explosive range; however, as it migrates, it is almost always diluted by air to combustible or explosive proportions. There are many tragic examples of methane explosions attributed to landfill gas migration. Table 1 lists documented cases of landfill gas migration or fires. When uncontrolled, landfill gases can migrate subterraneously as far as 1000 ft (300 m) into structures built on or near the landfill. This presents a very dangerous problem, not only because of the explosive hazard, but also because the carbon dioxide and methane present can displace air in enclosed areas (basements, manholes, etc.) and asphyxiate workers.

The U.S. Environmental Protection Agency (USEPA) regulations for controlling explosive gases from sanitary landfills are based on the methane concentrations in structures built on the landfill and in the soil at the property boundary.[4] For this type of application, concentrations are usually discussed in terms of a percentage of the Lower Explosive Limit (LEL). The LEL for methane is 5.53 percent (usually stated as 5 percent) by volume in air. The regulatory criteria state that the concentration of explosive gases generated by a facility shall not exceed 25 percent of the LEL (1.25 percent methane) in facility structures and 100 percent of the LEL (5.5 percent methane) at the property boundary. Figure 2 presents a decision flowchart for

[4] *Federal Register*, Vol 44, No. 179 (September 13, 1979), p 53438.

**Table 1**
**Examples of Documented Landfill Gas Explosions or Fires**

1. *Rockford, Illinois (1966-67)*–Methane gas from the Peoples Avenue Landfill migrated into the basement of the Quaker Oats production plant in concentrations that would support a flame. Control measures included the installation of vents to prevent methane from accumulating.

2. *Atlanta, Georgia (December 1967)*–Methane gas from an adjacent landfill migrated into a sealed basement of a single-story recreation center building (27 m x 12 m with a 15-m x 9-m addition). A lighted cigarette caused the methane to explode, killing two workmen, injuring six others, and completely demolishing the building.

3. *Montreal, Canada (1968)*–A parking lot was built on top of a closed landfill with lamps installed which were designed to vent methane gas from the landfill into the atmosphere. However, methane gas migrated under a swimming pool under construction and exploded, ripping it apart.

4. *Winston-Salem, North Carolina (September 1969)*–Methane gas migrated from an adjacent landfill into the basement of an armory. A lit cigarette caused the gas to explode, killing three men and seriously injuring five others.

5. *Southeast Oakland County, Michigan (1974-75)*–Methane from an operating landfill migrated into nearby homes and accumulated to explosive levels. Control measures included the construction of a gravel-filled trench between the landfill and housing area.

6. *Richmond, Virginia (January 1975)*–Methane gas from a nearby landfill migrated into an apartment, exploded, and injured two people. Control measures included the development of an active gas extraction system to protect the 1000 families living nearby and two schools which were found to be built on top of the landfill.

7. *Louisville, Kentucky (1975)*–Explosive concentrations of methane gas migrated into eight homes built near a landfill. Control measures included the development of a gas venting system.

8. *Sheridan, Colorado (1975)*–Methane gas from a landfill migrated into a drainage pipe under construction. A welding torch ignited the gas, injuring two workmen.

9. *Sheridan, Colorado (1975)*–Gas accumulated in a storm drain pipe that ran through a landfill. An explosion occurred when several children playing in the pipe lit a candle, resulting in serious injury to all the children.

10. *Shelbyville, Indiana (1976)*–An incinerator built on a landfill developed explosive levels of methane when the gas migrated into the structure.

11. *Commerce City, Colorado (1977)*–An explosion occurred in a tunnel being drilled under a railroad right-of-way near a landfill. The explosion was caused by a worker lighting a cigarette and resulted in both workmen being killed and four firemen being injured.

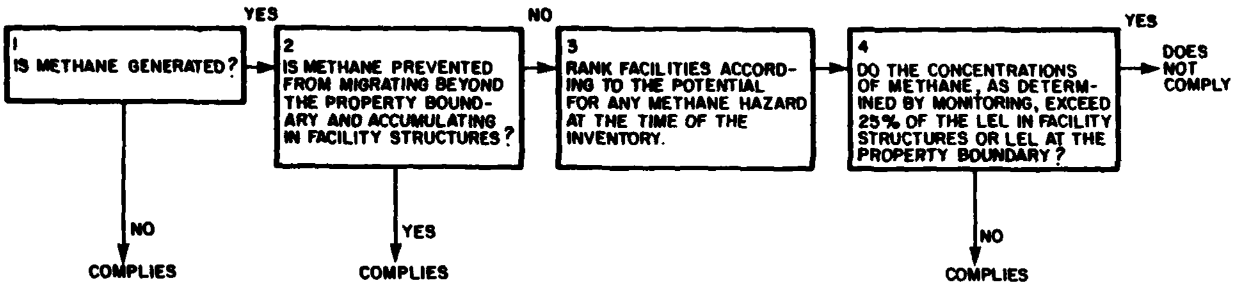


**Figure 2.** Flow chart for evaluation of safety in consideration of landfill gas formation. (From *Classifying Solid Waste Disposal Facilities, A Guidance Manual*, SW-828 [Office of Solid Waste, U.S. EPA, March 1980].)

explosive gases at a sanitary landfill. Failure to comply could result in the facility having to accept liability for any damage to adjoining properties and an "open dump" status for the landfill operation. Official designation of a facility as an "open dump" requires closure or immediate remedial action by the operating authority.

At Army installations, disposal sites that were constructed or operated before measures to correct or prevent gas generation and/or migration became common are of special concern, especially abandoned disposal sites or facilities constructed over organic fills. Additionally, recent advances in leachate control (e.g., liners) have increased the potential for gas problems at landfill sites, Army personnel will require information on recognizing, assessing, and dealing with these problems.

### Objective

The objective of this report is to provide any installation, MACOM and District engineer personnel with information about: (1) recognizing potential or actual landfill gas problems, (2) selecting gas-monitoring equipment and procedure for investigating potential landfill gas migration problems and selecting gas control strategies, and (3) using computer modeling to predict gas production migration and the success of gas control devices.

### Approach

The processes of gas generation and migration in landfills were summarized to provide a brief, informative overview. Methods for detecting and monitoring gas generated in landfills were reviewed in terms of equipment required, safety precautions which must be used in carrying them out, and a description of their capabilities. Active and passive gas control strategies were investigated and their advantages and disadvantages determined. The use of computer simulations for gas migration and control modeling was investigated and examples of their potential applications evaluated.

### Mode of Technology Transfer

It is recommended that information in this report be incorporated into Technical Manual 5-814-7, *Hazardous Waste Land Disposal/Land Treatment Facilities* and TM 5-634, *Solid and Hazardous Waste Collection and Disposal.* An Engineer Technical Note will also be issued.

# 2 GAS GENERATION IN LANDFILLS

### Gas Production

The bacterial decomposition of organic materials in an anoxic environment usually produces methane gas. Municipal solid waste (MSW) is made up mostly (50 to 80 percent) of degradable organic materials. Table 2 and Figure 3 give typical compositions of MSW. The organic material present is primarily cellulose due to the large percentages of paper. Cellulose, which is a polymer of glucose, is an excellent nutrient for several species of fungi and bacteria. Since typical MSW is quite porous even when compacted, large amounts of air (21 percent oxygen) will be present in the landfill; prior to the development of the anoxic environment required for methane generation, aerobic bacterial decomposition takes place in the landfill. Bacteria will aerobically digest cellulose, producing glucose, water, and other organic end products. Further aerobic decomposition can completely oxidize the glucose to carbon dioxide and water by the following reaction:

$$\underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6\,O_2} \rightarrow \underset{\text{carbon dioxide}}{6\,CO_2} + \underset{\text{water}}{6\,H_2O}$$

**Table 2**
**Composition of Municipal Solid Waste**

| Category | Myers and Others*,** | Jackson & Streng+,** | Chian and Others++,** | Eifert & Swartzbaugh†,** |
|---|---|---|---|---|
| Paper | 44.79 | 40.53 | 36.5 | 49.6 |
| Metal | 10.82 | 8.29 | 14.7 | 9.5 |
| Plastics, rubber leather | 9.03 | 6.52 | 2.8 | 6.0 |
| Glass | 7.61 | 7.42 | 6.8 | 12.0 |
| Textiles | 3.08 | 4.19 | 0.7 | 3.2 |
| Disposable diapers | 2.68 | 1.78 | – | 1.4 |
| Food waste | 0.94 | 7.53 | 14.4 | 7.3 |
| Wood | 0.49 | 0.86 | | |
| Garden waste | 0.41 | 15.32 | 3.1 | 4.6 |
| Ash, rock, dirt, fines | 20.15 | 5.48 | 14.9 | 5.4 |

*T. E. Myers et al., "Stabilized Industrial Waste in Landfill Environment," *Disposal of Hazardous Waste, Proceedings of 6th Annual Research Symposium*, EPA-600/9-80-010 (USEPA, 1980), pp 223-241.
**All values are percentages on a dry weight basis.
+A. G. Jackson and D. R. Streng, "Gas and Leachate Generation in Various Solid Waste Environments," *Gas and Leachate from Landfills: Formation, Collection, and Treatment*, EPA 600/9-76-004 (USEPA, 1976).
++E. S. K. Chian, F. B. DeWalle, and E. Hammerberg, "Effect of Moisture Regime and Other Factors on Municipal Solid Waste Stabilization," *Management of Gas and Leachate in Landfills*, S. K. Banerji (ed.), EPA-600/9-77-026 (USEPA, 1977), pp 73-86.
†M. C. Eifert and J. T. Swartzbaugh, "Influence of Municipal Solid Wastes Processing on Gas and Leachate Generation," *Management of Gas and Leachate in Landfills*, S. K. Banerji (ed.), EPA-600/9-77-026 (USEPA, 1977), pp 55-72.

These reactions take place until all the molecular oxygen in the landfill is depleted. If the supply of oxygen is restricted, facultative and anaerobic bacteria will take over. This first phase of aerobic decomposition can last from a few months to a year, depending on several environmental factors, and will eventually produce an anoxic environment in which the major microbial substrate will be cellulose and a variety of organic end products.[5] This substrate provides nutrients for acid-forming bacteria, which convert complex materials into simpler organic compounds, mainly organic acids. The methane-forming bacteria, called methanogens, then use the organic acids as substrate to produce methane gas and carbon dioxide as the final, stable end products.

[5]*Methane from Landfills: Hazards and Opportunities*, Symposium Proceedings, Denver, CO (March 21-23, 1979).

The methanogens are slow-growing organisms and are very sensitive to environmental conditions. Table 3 summarizes the optimal conditions for anaerobic decomposition. Unlike in an anaerobic digester, the critical environmental factors are not controlled in a landfill. Ground temperatures are usually too low for efficient methane production; however, the aerobic decomposition phase produces a great deal of heat

**Table 3**
**Optimal Conditions for Anaerobic Decomposition**

| | |
|---|---|
| Percent oxygen | 0% (no free oxygen available) |
| Temperature | 85 to 100°F (29 to 37°C) |
| pH | 6.8 to 7.2 |
| Moisture content | Greater than 40 percent |
| Toxic materials | None |

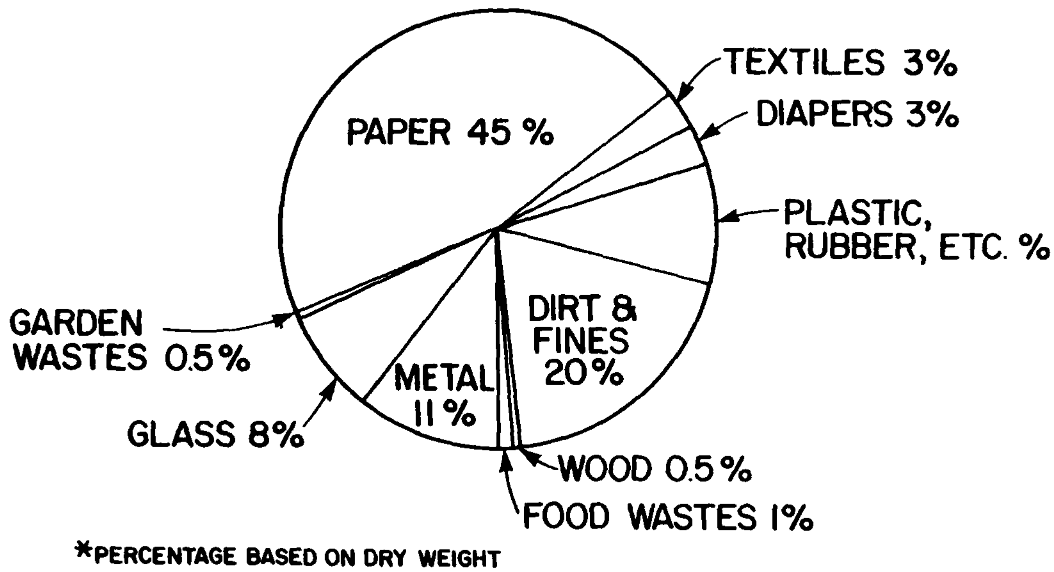


**Figure 3.** Typical composition of municipal solid waste. (From R. A. Shafer, et al., "Gas Production in Municipal Waste Test Cells," *Land Disposal of Municipal Solid Waste; Proceedings of 7th Annual Research Symposium,* EPA-600/9-81-002a [USEPA].)

which will usually bring the internal temperature of a landfill within the optimum temperature range for anaerobic decomposition and methane production (29° to 37°C).

**Moisture Requirement**

Moisture is required for all bacterial growth. To obtain optimum bacterial decomposition rates, the moisture content of refuse must be greater than 60 percent.[6] If the landfill is not located in an arid environment, the moisture content of the refuse will continue to be replenished, thus meeting the growth conditions required for methane-forming bacteria. A direct relationship between increasing moisture content and increasing gas production rates has been observed in laboratory test cells. In a study using small-scale landfill simulators, moisture contents were varied from 36 to 99 percent. Gas production rates increased from 2.1 to 17.9 mL/kg/day, with the highest gas production rate observed between the 60 to 78 percent moisture content range[7] (see Figure 4). At higher moisture contents, gas production rates leveled off. Moisture addition has been proposed to increase and speed up gas production to stabilize a landfill more quickly; however, the corresponding increase in potential leachate production in an uncontrolled environment makes this approach unfeasible. However, moisture addition could be used to stabilize methane production in a completely lined landfill having a leachate recirculation system. A system located in Lycoming, PA, uses a 20-mil membrane liner and a leachate collection system consisting of 7- and 8-in. (178- and 293-mm) perforated pipe laid above the liner. Leachate is collected at the toe of the landfill and drained into two lined, aerated lagoons. It is then pumped back into the working face of the landfill and injected into the landfill through 15-ft-(4.5-m)-deep trenches. This recirculation of leachate was credited with the rapid production of methane

[6] S. C. James and C. W. Rhyne, *Methane Production, Recovery, and Utilization from Landfills* (USEPA).

[7] F. B. DeWalle, E. S. K. Chian, and F. Hammerberg, "Gas Production from Solid Waste in Landfills," *Journal of the Environmental Engineering Division (JEED),* Vol 104, No. EE3 (American Society of Civil Engineers [ASCE], June 1978).

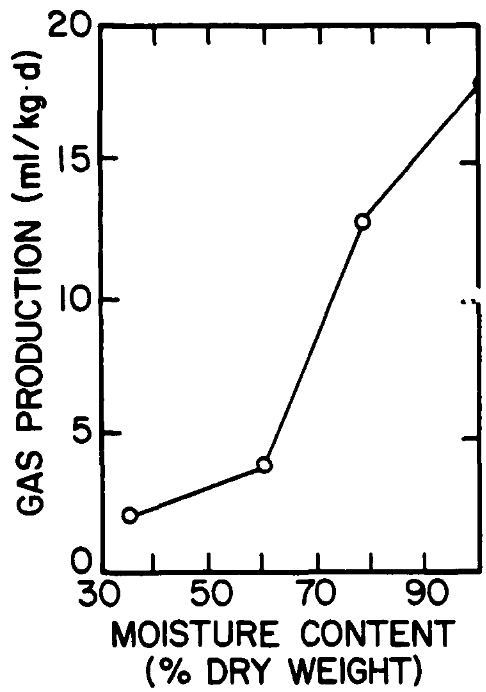


**Figure 4.** Variation in gas production with increasing moisture content. (From F. B. DeWalle, E. S. K. Chian, and E. E. Hammerberg, "Gas Production from Solid Waste in Landfills," *Journal of the Environmental Engineering Division [JEED]*, Vol 104, No. EE3 [American Society of Civil Engineers (ASCE), June 1978].)

gas, which exceeded 40 percent by volume of air (and therefore exceeded the explosive range) within 18 months of the landfill's opening.[8]

#### Time Required for Methane Production

Landfills that are more than 2 years old will usually produce substantial concentrations of methane. Numerous studies using lysimeters and pilot-scale landfill systems have recorded initial methane generation beginning after 300 days of completing and closing the test cells. A lysimeter study conducted by the Waterways Experiment Station (WES) resulted in methane generation by the 250th day of test cell operation.[9] The State of California conducted a study using a pilot-scale landfill. The test site contained 22,950 cu yd (17,534 $m^3$) of municipal (residential) refuse spread over three-quarters of an acre at depths between 18 and 25 ft (5.4 and 7.5 m). Again, dramatic initial methane generation was observed after the landfill had been completed and closed for 250 days. Figure 5 shows the results of this study. Table 4 shows the production of methane and its relation to other gases in a typical landfill as a function of time. The time required for methane generation to begin in substantial quantitites in a typical landfill is site-specific and generally unpredictable. Environmental conditions such as temperature, precipitation, seepage, composition of the refuse (especially moisture content), and in-place density are very important in determining when methane generation will be initiated. The mode of construction at the landfill and the type of final cover can also significantly affect the time required for an anoxic environment to evolve in the landfill and support methanogenic activity. Significant methane generati . and possible methane migration can be expected after 2 years of closing a landfill, but the earlier appearance of methane should not be ruled out.

Table 5 shows the typical composition of landfill gases. Methane is being produced in relatively high

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[8] R. S. Shafer, P. G. Malone, and J. E. Lee, ***Investigation of Landfill Gas Migration Near Markham School and George Washington Village, Fort Belvoir, VA*** (August 1980).

[9] *Classifying Solid Waste Disposal Facilities, A Guidance Manual*, SW-828 (Office of Solid Waste, USEPA, March 1980).

**Table 4**
**Variation Composition in a Typical Landfill Gas (From *Methane from Landfills: Hazards and Opportunities*, Symposium Proceedings, Denver, CO, March 21-23, 1979.)**

| Time Since Refuse Burial | Volume % | | |
|---|---|---|---|
| Months | $N_2$ | $CO_2$ | $CH_4$ |
| 0-3 | 5.2 | 88 | 5 |
| 3-6 | 3.8 | 76 | 21 |
| 6-12 | 0.4 | 65 | 29 |
| 12-18 | 1.1 | 52 | 40 |
| 18-24 | 0.4 | 53 | 40 |
| 24-30 | 0.2 | 52 | 48 |
| 30-36 | 1.3 | 46 | 51 |

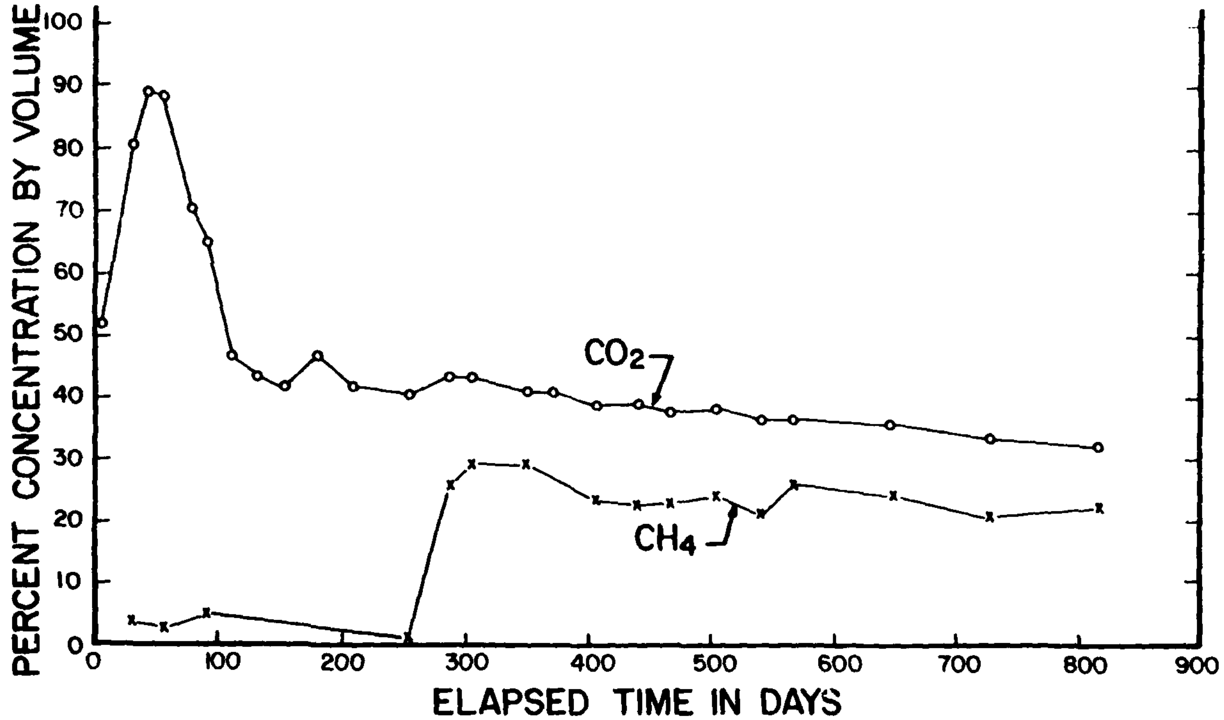


**Figure 5.** Variation in carbon dioxide and methane concentrations in a typical landfill with increasing time since burial. (From *In-Situ Investigation of Movements of Gases Produced from Decomposing Refuse*, Third Annual Report [California State Water Quality Control Board, December 1964].)

concentrations (greater than 40 percent) which are outside of its explosive range (but inside its combustion range); however, as it migrates and is diluted by air, it will enter the explosive range of 5.5 to 14 percent by volume in air. Attempts at determining gas production rates have been made with various degrees of success. These rates should not be considered absolute when applying them to an actual landfill. In lysimeter studies, gas production was as high as 69.5 mL/kg/day (dry weight), with average

**Table 5**
**Variation in Landfill Gas Composition Measured at Mountain View, California, Landfill (From S. C. James and C. W. Rhyne, *Methane Production, Recovery, and Utilization from Landfills*, USEPA.)**

| | Gas Composition (Volume %) | | |
|---|---|---|---|
| | Average | High | Low |
| Methane | 44.03 | 46.49 | 41.38 |
| Carbon dioxide | 34.20 | 36.80 | 30.73 |
| Nitrogen | 20.81 | 23.51 | 19.98 |
| Oxygen and argon | 0.96 | 1.69 | 0.48 |

values at 61.7 mL/kg/day.[10] These values are higher than those obtained from actual landfills, which ranged between 22 and 45 mL/kg/day.[11] Attempts have been made to use the higher production rates to determine a landfill's methane-generating capability, but many variables must be considered. The accessibility of degradable organic materials due to factors such as impermeable coatings or close packing and environmental factors (temperature, precipitation, barometric pressure) will make the methane generation capability of a landfill very uncertain. Studies assuming constant gas loss rate from landfills of 20 mL/kg/day have calculated the methane-generating capability of a landfill at about 17 years.[12] In another study performed on a pilot-scale system, the estimated methane

[10] T. E. Myers, et al., "Stabilized Industrial Waste in a Landfill Environment," *Disposal of Hazardous Waste, Proceedings of 6th Annual Research Symposium*, EPA-600/9-80-010 (USEPA, 1980), pp 223-241.

[11] Personal observation with R. Shafer (WES) and COL J. F. Moore, Facility Engineer Fort Belvoir, VA.

[12] F. B. Dewalle, E. S. K. Chian, and E. Hammerberg, "Gas Production from Solid Waste in Landfills," *Journal of the Environmental Engineering Division [JEED]*, Vol 104, No. EE3 (ASCE, June 1978).

generation capacity was based on the total carbon present in the landfill and the rates at which carbon is transported from the landfill, assuming that the initial amount of carbon was "available." The half-life of the landfill (time for half of the carbon present to be used) based on the carbon present and leaving was estimated at 57 years. It was further projected that for 90 percent of the carbon initially present in the landfill to leave would require 950 years.[13] It should be noted that this particular study was on a pilot scale, and factors such as "aerobism" inhibiting the anaerobic digestion and methanogenic activity should be considered. With the uncertainties involved, one must assume that active biological decomposition in a landfill will continue indefinitely. Therefore, abandoned and forgotten landfills, especially those constructed before 1970 when little consideration was given to site boundary conditions, may still be actively producing methane.

# 3 GAS MIGRATION

### Pressure Head

Landfill gas migration is the result of two processes: convection and diffusion. Convection is the movement of landfill gas in response to pressure gradients developed in the landfill. Diffusion is the movement of methane from areas of higher to lower concentration. The decomposition reactions produced by methanogens in confined areas can produce relatively high gas pressures. This would make construction of a gas-tight landfill infeasible. However, the normal landfill construction practice of alternating layers of refuse with 6-in. (152-mm) soil layers and finishing the landfill with a compacted clay cap of 1 ft. (.3 m) or more can present substantial barriers to vertical migration of the landfill gas. This can cause high gas pressures to develop, and pressure gradients will move the gas laterally from the landfill through pathways of least resistance. At one Virginia landfill, methane was seen bubbling violently through 3 ft (.9 m) of water in a shallow boring. The boring was sealed with a clay plug, but the plug was blown off within 5 minutes.[14] Methane migration is also restricted by its relative insolubility in water. The presence of a high or perched water table, which is relatively common under landfill sites, can inhibit the depth of gas migration and influence lateral migration. Changes in the water table can also cause gas pressure to fluctuate.

### Diffusion

Since methane is lighter than air (0.544 times as dense), it will normally diffuse upward through the refuse cells, out through the cover, and into the atmosphere. However, if this upward movement is inhibited, the landfill gas can diffuse laterally to areas of lower concentration. The factors influencing lateral migration are varied and site-specific. They include:

1. Type of refuse cell construction used during placement of the refuse

2. Final cover placed on the landfill

3. Landfill age and gas generation rate

4. Presence of natural and man-made conduits and barriers

5. Climatic or seasonal environmental variations.

In the past, it was common to use an area fill practice to bury refuse. Very little effort was used on individual cell construction, and not covering the refuse daily was common. In this type of landfill there is very little to prevent the vertical migration of gas, especially when the final cover is thin, cracked, or nonexistent. One could assume that there would be no lateral migration and that only minimal protection, such as a clay barrier between adjacent structures and the landfill, would be needed. This assumption might be valid most of the time, but one must consider what can happen if the top refuse layer or cover material becomes saturated or frozen. The thawed, dry soil under any structure on the landfill would provide a relatively porous medium and an excellent pathway for gas to migrate out of the landfill into any structure on the fill.

Quite often, the intermediate and final landfill cover will be constructed of compacted clay material to restrict water infiltration. When the surrounding soils are composed of more porous materials, such as sands and gravels, the methane is forced to move laterally toward areas of lower pressure or lower gas concentration.

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[13] *In-Situ Investigation of Movements of Gases Produced from Decomposing Refuse*, Third Annual Report (California State Water Quality Control Board, December 1964).

[14] D. O. Nuttall, "Control of Gas Migration in Urban Landfills," *Public Works*, (July 1980), pp 46–49.

Theoretically, methane production never stops, but rather decreases to a very small rate; this makes it very difficult, if not impossible, to estimate how long a landfill will generate methane. The factors that control decomposition rates, such as moisture content, pH, and temperature, vary too much to make generalizations. It must be remembered that even after methane generation falls to an unmeasurable level, residual methane can still diffuse out of the landfill and present a potential hazard.

**Corridors for Gas Movement**

Natural and man-made corridors for gas migration are quite common around landfill sites. Most landfill explosions are fueled by these methane corridors. Water conduits, a steel drain culvert, and buried utility lines running near landfills all provide corridors for methane migration. It is not uncommon to see high methane readings in water meter pits by houses where the water line runs near a landfill. Cracked or leaking subsurface utility structures, such as sewer manholes or catch basins near landfills, can also provide migration corridors and areas in which methane can accumulate. Identifying these structures when identifying potential landfill gas hazards is very important, since they not only provide an area for methane to accumulate, but also areas in which children play and hide. All storm sewers, culverts, and any structures large enough for a child to get into should be screened off or barricaded when a landfill is identified or built in a populated area.

Natural corridors for methane migration include gravel and sand lenses. Also, landfill differential settlement can produce void spaces, cracks, and fissures which can reduce subsurface gas pressures in their immediate vicinity. Thus, they not only provide pathways for methane migration but also promote migration to areas of reduced gas pressure.

Natural and man-made barriers can include clay deposits, a high water table, roads, or railroad compacted subgrade. Any condition that makes soil denser (less permeable to gas migration) can [illegible] considered a barrier. These barriers tend to hide [illegible] generation problem since they are typically [illegible] to the depth of the landfill and are [illegible] gas control. At one Virginia landfill, a [illegible] ited a partial gas barrier between a housi[illegible] landfill. Gas readings near the soil surface on [illegible] housing side of the road indicated that no methane was present. The road and subgrade were thought to be acting as a barrier to gas migration. However, a sand lens was located 3 to 4 m below the road, so this was not the case. When a boring was made into the sand lens adjacent to the housing foundations, about 65 m from the landfill boundary, methane concentrations were found to be almost 50 percent.

**Seasonal Variation**

Changes in moisture and temperature can greatly influence methane generation and migration rates. Thus, methane migration can be seasonally dependent. The wet seasons of the year can increase lateral migration for two reasons. First, the water infiltrates the refuse and increases the moisture content, thus boosting the gas production rate. A selective gas solution can even increase the methane concentration of the decomposition gas mixture by removing carbon dioxide. Second, the saturated soil slows vertical gas migration. Together, these two factors increase lateral migration. If the soil freezes, lateral migration will also increase, since the frozen water in the soil void spaces will be a natural barrier to vertical migration. Cold air temperatures will not usually slow gas production, since the landfill's internal temperature is not greatly influenced by the ambient air temperature. The barometric pressure can also influence gas migration, since increasing atmospheric pressure will impede vertical migration, and decreasing pressure will allow more vertical migration or "outgassing" of the landfill. Generally, high gas readings directly over a landfill can be expected on hot summer days immediately after a storm (low barometric pressure), and low readings during frozen or saturated soil conditions or under a high barometric pressure.

# 4 GAS DETECTION AND MONITORING AT LANDFILLS

**Legal Requirement**

The liability resulting from damage caused by landfill-generated methane is not clear-cut, because tracing the source of the gas is a problem. However, at Army installations, the owner, operator, waste generator, and custodian of the closed landfill are associated with the military facility, so the liability may be with the facility. Therefore, Army personnel must decide how large an area should be protected from landfill gas migration. All structures built on the landfill should be protected from gas migration. Most State and local building codes require protecting and

monitoring structures built on closed landfill sites. Typically, structures built within 300 m of a landfill area can be considered potentially hazardous. Therefore, when a closed landfill is located and gas is thought to be migrating off-site, a comprehensive gas control plan should be developed that will include all structures within a minimum of a 300-m radius of the site. Gas migration is very site-specific, so the differences in soil types and in natural and man-made barriers and corridors for gas migration can influence how much and how far methane will migrate from the landfill site. Each site should be judged separately after a comprehensive gas survey.

**Gas Detection**

Basically, there are two ways to investigate gas problems. One is considered to be preliminary and the other comprehensive. If a problem is suspected due to the occurrence of peculiar odors, differential settlement, cracked foundations and sidewalks, or vegetative stress, a preliminary investigation should be initiated to determine:

1. Presence or absence of a landfill

2. Presence of gas in the landfill

3. Presence of off-site gas migration

4. Presence of gas in adjacent structures

5. Determination of additional study requirements.

If a preliminary investigation shows that a potential hazard exists, then a more comprehensive quantitative study should be conducted to determine:

1. Position of the landfill boundary

2. Amount, type, and condition of the buried refuse

3. Magnitude and extent of off-site gas migration

4. Landfill gas production rates

5. Presence and extent of real or potential hazards

6. Development of remedial action alternatives and control strategies.

The comprehensive investigation should incorporate two general approaches: a survey and a field investigation. The survey should include:

1. A "walk-over" of the area to visually determine signs of differential settlement, litter, refuse coming to the surface (e.g., tires), odor, vegetative stress, leachate staining, and any other signs that will define the landfill boundaries.

2. Interviews with landfill operators or refuse truck drivers to determine types of refuse placed, cell construction used, compaction methods and cover material used, dates of starting and closing the landfill, and any information on the geology of the area, such as water table depth and types of surrounding soils.

3. Interviews with area residents and facility personnel to determine dates and locations of the landfill operation.

4. A review of aerial photograph coverage from different time periods to determine location and dates of landfill operations.

5. Interviews with utility companies and the Facilities Engineering staff to determine the location of underground utility lines and to gather information regarding any problems encountered when installing the lines near the landfill.

6. A review of area construction plans that might show soil borings and indicate which structures have crawl spaces, basements, subslab ducts, or other features that allow gas to migrate into and collect inside structures on or near fill sites.

7. A review of U.S. and State geological survey publications regarding the site's geology and groundwater hydrology. Monitoring well records at suspected landfill sites can be used to develop data on the groundwater quality and the depth of the water table.

After the utility lines are located and the approximate landfill boundary established, a full field investigation should be conducted which should include:

1. A gas meter survey of all structures on and within 300 m of the landfill boundary to determine the absence or presence of gas in basements or crawl spaces, foundation openings, utility entrances to the structures, and any other area that would allow gas to migrate and/or collect.

2. A gas meter survey of all culverts, manholes, caves, or excavations within 300 m of the landfill perimeter to determine the presence of methane gas.

3. A drilling program to define the landfill boundary, cover thickness, depth and type of refuse, and depth to the water table.

4. A gas monitoring program in selected wells in and around the landfill to determine gas migration over time and determination of gas production rates using a flux box technique (see pp 38–41).

The data collected should indicate the presence or absence of a potential hazard and provide a basis for selecting remedial measures to safeguard properties within or adjacent to the landfill site.

**Gas Meter**

A portable combustible gas meter is necessary for any landfill gas investigation. These meters have greatly simplified landfill monitoring because the sample does not have to be returned to a lab for gas chromatograph analysis. These meters can be used in a permanently installed continuous mode of operation to give an early warning of the presence of methane in a structure or other enclosed area. The combustible gas meters measure methane concentrations using one of two systems (or in some cases, both systems). Low methane concentrations (below the LEL) are measured using a catalytic heating system. As air is drawn into the instrument, the combustible content of the gas is burned catalytically on the surface of a catalytic (hot-wire) filament. The heat generated by combustion on the hot wire provides a variable resistance to the meter readout. Atmospheres above the LEL (5 percent methane in air) are checked by using a thermal conductivity filament to measure the relative thermal conductivity of the sample compared with air. Instruments incorporating both the hot-wire and thermal conductivity measurement systems are very helpful when working in landfill-generated gas atmospheres because the catalytic combustion instrument is limited in oxygen-deficient atmospheres. When an instrument is in the catalytic combustion operating mode, valid readings can be obtained in the 0 to 100 percent LEL (i.e., 0 to 5 percent methane). However, if the sampled air does not contain enough oxygen to support combustion on the catalytic filament, the meter will show an erroneous reading of zero, when in reality, the atmosphere might contain 50 percent methane and 50 percent carbon dioxide, a common condition in a landfill environment. Therefore, a dual detection meter should be used.

When operating a gas meter, initial readings are taken using the catalytic combustion filament until 100 percent LEL is reached; then the meter is switched to read 0 to 100 percent methane, using the thermal conductivity meter. If zero LEL readings are encountered and oxygen deficiency is suspected, the meter should be switched to read percent methane on the thermal conductivity meter. When using any type of combustible gas meter, the manufacturer's instructions should be followed very closely. All personnel who use the instrument should become familiar with the operating procedures, care, and limitations of each meter. It is also very important that these meters be calibrated periodically. Most companies offering combustible gas indicators also have inexpensive calibration check kits. The importance of these calibration checks cannot be overstated, since the thermal conductivity and catalytic filaments can become poisoned very easily in landfill gas environments, and instrument sensitivity is then lost. It is usually a simple and inexpensive task to replace the damaged filaments.

**Bar Hole Punch**

Typically, an initial "walk-over" of a site will incorporate the use of a bar-hole punch or a simple hand auger to make shallow borings and obtain gas samples. The bar-hole punch is a metal rod which is driven into the ground and then removed, leaving a small hole. (The same results can be obtained with a small hand auger.) These small holes have limitations. The sample volume is small because the hole is usually less than 3 ft (.9 m) deep and 1 in. (25.4 mm) in diameter. Sample contamination by atmospheric air is very likely and the exact sampling point is not relocatable. Therefore, the results obtained should be used only to determine the presence of methane in the limited depth of the hole. Any quantitative analysis of shallow methane or determination of methane deep in the landfill should be made using flux box techniques or cased monitoring wells.

**Gas Monitoring-Wells**

The installation of gas monitoring wells has many advantages. When the borings for the wells are augered, information regarding the cover thickness, the thickness, condition, and type of refuse, and the depth to water table can be logged. Once the well is installed, methane concentrations can be measured over a period of time and under changing environmental conditions. Monitoring wells installed off the perimeter of the landfill will indicate gas migration and should be monitored over a period of time to determine the effects of changing environmental conditions, such as frozen or saturated soil and changes in barometric pressure. Monitoring wells should also be installed off

the landfill perimeter at different depths when there may be gravel or sand lenses or any other naturally occurring pathways for methane migration.

The unpredictable nature of methane migration makes it very difficult to monitor, and only when as many variables as possible are considered can the potential hazards be fully recognized. Typically, a gas monitoring well will be constructed with 2-in. (51-mm) PVC pipe. Figure 6 illustrates a gas monitoring well installed at Fort Belvoir, VA. These gas monitoring wells were constructed by augering a 4-in. (102-mm) boring and placing the 2-in. (51-mm) PVC well casing in the unsaturated zone. The bottom section of the casing was made up of slotted PVC pipe to allow free exchange of gases between the interior of the well and the surrounding soil. Sand or gravel was backfilled around the slotted casing, and clay was backfilled and taped to the surface to keep atmospheric air from being drawn into the well. A steel well protector, with a hinged and locked steel cap, was set in concrete over the end of the casing to guard against vandalism. A one-hole stopper was placed in the top of the casing and a section of tygon tubing was attached to allow gas to be drawn from different depths in the well. The tubing was closed with a pinch clamp to prevent gas from moving up and out of the casing.

**Flux Box**

A simple, inexpensive technique has been developed using a flux box to measure the rate at which methane leaves the surface of a landfill. Flux boxes are made from 55-gal (208-L) drums or any similar container. The container traps gases leaving the landfill surface, allowing the gas concentration to be measured over a period of time. The flux box is made by imbedding the open end of the drum into the surface of the landfill. Care should be taken to make sure there are no gaps between the surface and edge of the drum that would allow outside air to enter. The closed end of the drum is fitted with two sampling ports. During measurements, one port is left open to attain equilibrium between the pressure in the drum and the atmosphere. The second port is connected to a portable methanometer or other combustible gas detector.

Once the drum is in place, methane measurements are taken over a period of time (e.g., every minute for 15 minutes). Since the volume of the flux box and the area of the soil surface covered by the box are known, the rate of methane leaving the landfill surface per unit area can be calculated. The rate of methane leaving will vary considerably by location and over time with changing environmental conditions. Porous or fractured areas will vent more gases than others. Decreasing atmospheric pressure will also allow more gases to be vented. Therefore, flux box measurements should be made at several locations. They should be made either during periods of relatively constant atmospheric pressure, or over several days to average the effects of atmospheric pressure changes.

A study conducted at the Fresh Kills Landfill on Staten Island by the New York State Department of Health used flux boxes made from halves of 55-gal (208-L) metal drums. The variability associated with flux box measurements was observed at this site at 21 different locations during 5 days in September and October. A number of locations showed little or no methane being released from the surface, while a few locations were venting methane at more than three times the average rate.[15]

**Monitoring in Structures**

While a "cookbook" approach to assessing the magnitude and extent of gas migration into structures on or near a landfill might be desirable, it cannot be justified due to the lack of knowledge about various building designs and the site-specific characteristics of landfill disposal sites. Both on-site structures and structures built near the landfill (within 300 m of the landfill boundary) should be considered potential hazards and treated as such when surveying for methane gas.

Structures should be monitored with augering equipment for combustible gases at and near their foundations. Care must be taken to locate all utility lines before any drilling. Areas where the utility lines enter the structure should be surveyed thoroughly, since the utility line trenches provide migration pathways. Cracks in the foundation or areas of differential settlement in the soil near the foundation should be sampled, since these fractures and fissures can provide corridors for gas movement. Basements or crawl spaces under floors should be surveyed with great care, since these areas provide spaces for large volumes of methane-air mixtures to collect.

[15]C. Kunz and A. H. Lu, "Flux-Box Measurements of Methane Emanation from Landfills," *Symposium Proceedings, Methane from Landfills: Hazards and Opportunities*, Denver, CO (March 1979), pp 21-23.

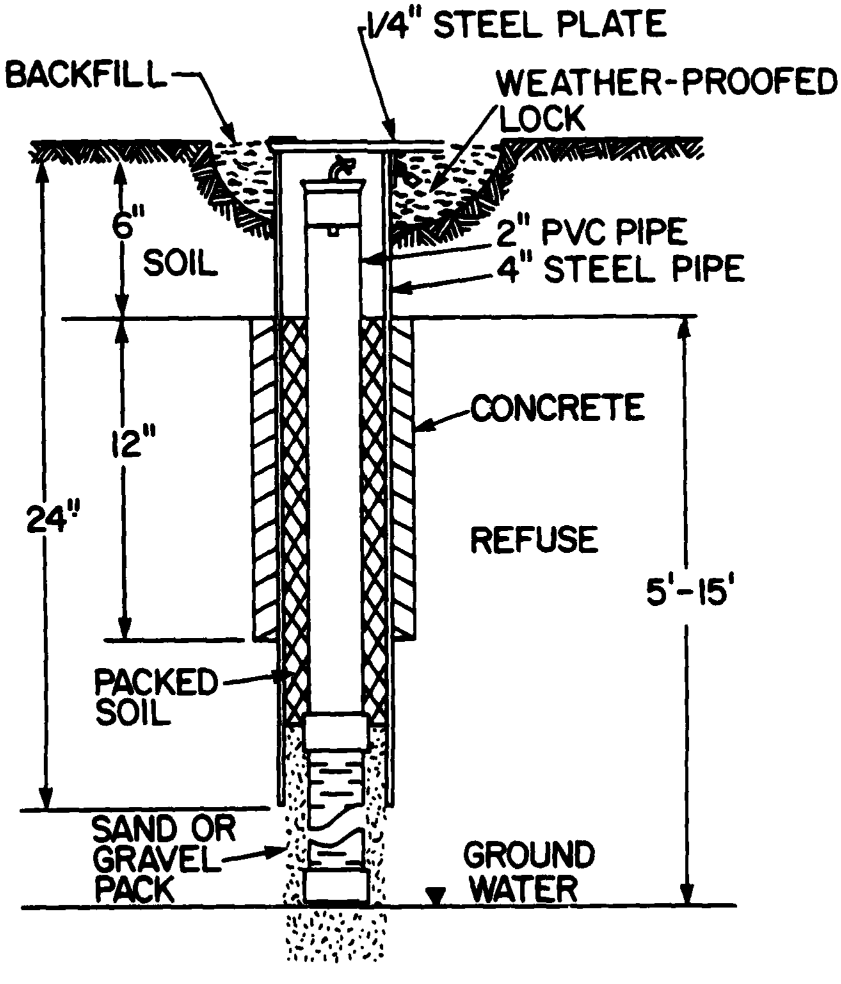


**Figure 6.** Design of gas monitoring wells. (From R. A. Shafer, P. G. Malone, and J. E. Lee, *Investigation of Landfill Gas Migration Near Markham School and George Washington Village, Fort Belvoir, VA* [August 1980].)

Carbon dioxide and methane are usually produced in equal amounts in a landfill and will displace oxygen from confined areas. Therefore, extra safety precautions (either an oxygen meter or some kind of breathing apparatus) should be used when investigating enclosed areas.

In buildings with slab-on-grade construction, heating and air-conditioning ductwork will often be installed under the slab. If this ductwork corrodes, it can provide an entrance for methane to migrate into a building; where possible, all such ductwork should be surveyed for combustible gas. Areas in the structure itself that do not have ventilation, such as closets or the areas above false ceilings, also provide spaces for methane (which is half as light as air) to migrate and collect.

Monitoring of structures should not be limited to surveying only the buildings on or near landfills. Manholes, culverts, and storm sewers should also be monitored, because they all provide pathways for methane migration and areas for the gas to collect. Any new construction or excavations near the landfill should also be surveyed. If any trenching operations intercepted sand or gravel lenses carrying methane off-site, a potentially hazardous atmosphere could develop when oxygen is displaced and landfill gas enters the trench.

#### Personnel Safety While Monitoring Landfills

Work parties should consist of at least two people. Explosimeters, methanometers, or any other combustible gas indicator should be in good working order and have a well-charged battery pack; personnel should understand and follow the manufacturer's operating instructions. The instrument should be certified as explosion-proof and should have been calibrated recently. If monitoring will be done in confined areas, an oxygen meter should be provided along with breathing apparatus (not gas masks). Confined areas should be sampled for flammable gas and low oxygen levels before entering. Shoes with nonmetallic soles should be worn to prevent sparks. Also, when opening access covers into utility lines or manholes, care should be taken not to cause a spark between the metal cover and ring. Smoking and open lights should not be allowed around the survey area. Further precautions should be taken when working with drilling equipment in the landfill. A foam fire extinguisher and a combustible gas indicator should be on hand at all times. The drill rig should be placed with the engine upwind of the boring to prevent the sparks from the engine from igniting any gas that might be venting from the hole. Standard hard hats, goggles, and steel-toed shoes should also be worn.

#### Continuous Monitoring Systems

Continuous monitoring systems are available for measuring explosive gases in structures built on or near landfills. Typically, these systems incorporate one monitoring board in a central location, and several (as many as 20 or more) detector heads in different areas of the structure. The detectors are placed in areas where methane can collect, such as above false ceilings, and inside crawl spaces and utility closets. Depending on the construction practices used, the detectors can also be placed underneath the slab to indicate whether any methane is migrating into the structure. These systems typically have a low-level warning (5 percent LEL) that can be remotely monitored at a fire station or other central location and a high-level alarm (20 percent LEL) that will sound in the structure. As with any other gas monitor, the system is only as good as its calibration, so all manufacturer's instructions should be followed. When a system is purchased, a manufacturer's representative will usually help select the monitoring locations. One problem with these systems is that any combustible vapor can trigger the alarm. For example, normal janitorial duties, such as waxing a floor, can set the alarms off; however, scheduling and appropriate communication can easily solve this problem.

## 5 GAS CONTROL STRATEGIES

Gas control systems may be either passive (relying on natural pressure or concentration gradients) or active (providing protection by using blowers or wind vents to create a positive or negative pressure gradient). The choice depends on site conditions. Passive systems can be effective in controlling convective gas flow, but not diffusive flow. Active systems are effective in controlling all types of gas migration, but are usually more expensive to build, operate, and maintain.

#### Passive Systems

Passive gas control systems have been used on existing and new landfills with varied success. These systems include gravel-filled trenches, perimeter rubble vent stacks, and/or combinations of these. Passive systems can also incorporate impermeable barriers. Lateral gas movement can be controlled by providing

a pathway that is always more permeable than the surrounding soil. Since the permeable material (gravel) offers a path more conducive to gas flow than the surrounding medium (soil), flow is directed through the venting structures to the atmosphere.

If venting trenches are used, they should be deeper than the landfill to make sure they intercept all lateral gas flow. If possible, the trench should be tied into an impermeable zone, such as the permanent water table, or into continuous impermeable geologic units. The trenches may be backfilled with crushed rock, gravel, sand, or similar materials. The material should be graded to prevent infiltration and clogging from soil carried in by the water. Filter fabrics can be useful in preventing clogging of the gravel vents. To insure ease of gas flow, fines should be avoided in the backfill material (less than 5 percent passing No. 100 sieve). If possible, the trench should be built so that it drains naturally; in some cases, tile has been used in the bottoms of the trenches. The surfaces of gravel trenches should be kept free of soil and vegetation that would hinder gas venting. Figure 7 shows a typical gravel vent and trench.

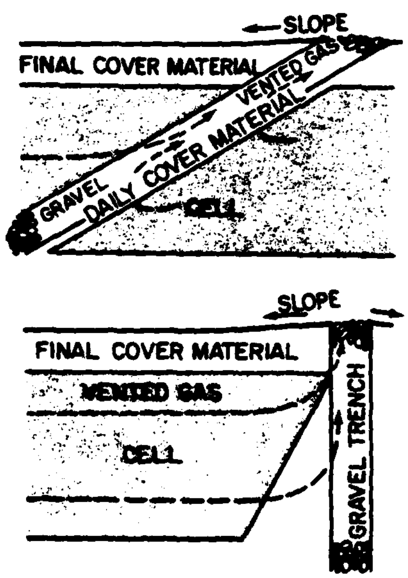


**Figure 7.** Gravel vent and gravel-filled trench used to control lateral gas movement in a sanitary landfill. (From D. R. Brunner and D. J. Keller, *Sanitary Landfill Design and Operation*, Environmental Protection Publication SW-65tS [USEPA, 1971].)

The rubble vent stack is another type of passive system. These are large borings (36 in. [914 mm] or more) that are backfilled with crushed rock, gravel, or similar materials. The vents are installed along the perimeter of the landfill (at distances depending on the vent's radius of influence) and should intercept lateral gas movement as a gravel trench would. When constructing the vent stack, installation of perforated PVC pipe in the boring (Figure 8) will provide the option of using the vent as an active extraction well for gas recovery or control. In still another passive system, vent pipes are installed through the landfill's relatively impermeable top cover or cap (Figure 9). Collecting laterals are placed in shallow gravel trenches within or on top of the waste and connected to vertical risers. The sizes and spacings required are site-dependent and are determined by the gas production rate and gas permeability of the cover and surrounding soil. In some cases, the vertical risers have been equipped with a flare system to ignite vented gas. The risers should be tamper-proof and extend above normal reach to minimize chances of accidental ignition of gas. Risers should not be placed near buildings, but if such placement is unavoidable, they should discharge above the roofline.[16]

Even without an impermeable liner, passive systems can control convective gas flow; however, they are less effective or sometimes totally ineffective in controlling diffusive gas flow. Diffusing gas will move directly through the more permeable material of the gravel trench by diffusion into the surrounding soils and will not vent upwards into the atmosphere. This phenomenon was illustrated in a computer model study at Ohio State University that evaluated various gas migration control systems on landfills. The study determined that in terms of natural convection, the gas migration results for an unlined passive trench installed at different depths in coarse, grained soil could not be distinguished from having no trench at all. The results for the same landfill and trench configurations installed in fine, grained soil showed measurable, but small effectiveness.[17]

[16] D. R. Brunner and D. J. Keller, *Sanitary Landfill Design and Operation*, Environmental Protection Publication SW-65tS (USEPA, 1971).

[17] C. A. Moore, I. S. Rai, and J. Lynch, "Computer Design of Landfill Methane Migration Control," *JEED*, Vol 108, No. EE1 (ASCE, February 1982).

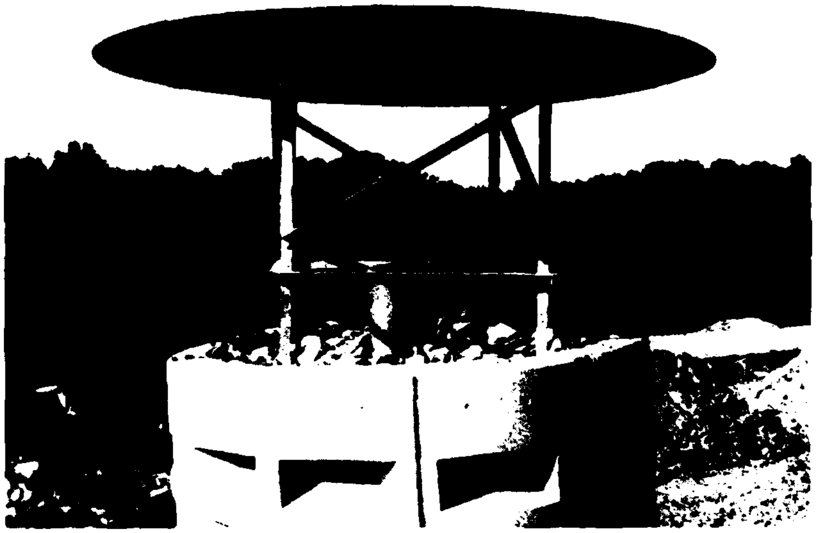

**Figure 8.** Gas vent in place at Lycoming, PA, landfill.

There are three types of impervious liners for containing gas flow: synthetic liners, admixed materials, and natural soil. Synthetic liners are manufactured from rubber or plastic compounds. Polyvinyl chloride (PVC) liners are frequently used because they are more impermeable to methane in comparison to polyethylene and are relatively inexpensive. The integrity of the impermeable membrane is critical, and it must be installed and sealed with great care. The membranes must be put down so as to avoid punctures, and usually layers of soil or sand must be placed on both sides.

Admixed materials, such as asphaltic concrete, are also used as liners for gas control. Asphalts have the advantages of being universally available, relatively inexpensive, and able to maintain their integrity under structures. They have the disadvantages of being more permeable than synthetic membrane liners and having a tendency to crack under differential settlement. Natural soil, particularly clay, can be used as a barrier to gas movement. Clay liners have the advantages of being readily available and inexpensive. However, for a clay liner to be effective, the soil must be kept nearly saturated. A clay gas barrier should be 18 to 48 in.

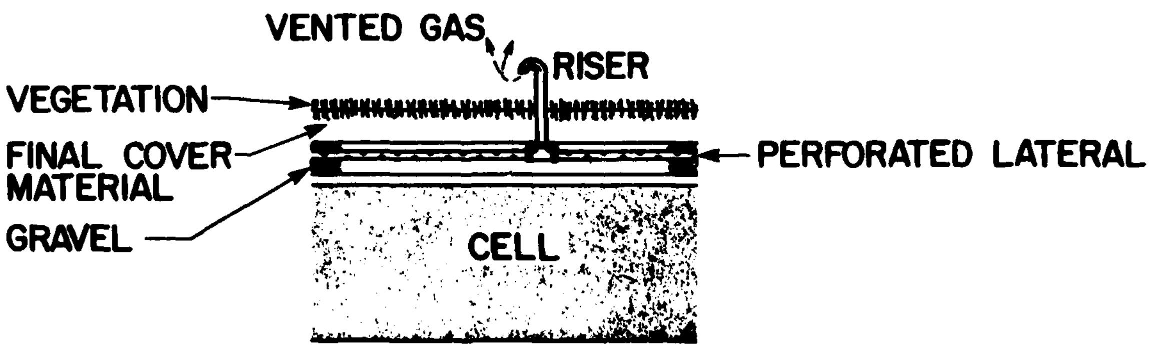


**Figure 9.** Pipe vent with connecting laterals in shallow gravel trenches above the waste. (From D. R. Brunner and D. J. Keller, *Sanitary Landfill Design and Operation,* Environmental Protection Publication SW-65tS [USEPA, 1971].)

(457 to 1219 mm) thick, should be continuous, and should not be penetrated by solid waste or outcropping of surrounding soil or rock. Prolonged exposure to air will dry the material and cause the clay to shrink and crack. Like admixed materials, clay barriers tend to crack under differential settlement. Off-site clay materials, such as commercial bentonite, may also be used for gas control when onsite soils are not suitable.[18]

Barriers are best installed during landfill construction, since later work is often more costly, and sometimes totally impossible (usually the case with barriers beneath structures built on a landfill). As shown in Figure 10, the impervious membrane is generally placed along the bottom of the trench and on the trench wall away from the landfill. A shallow landfill and high water table are typical of conditions for this type of system. If the trench is open, the liner material is attached at the top of the outside wall; however, if vent stacks are used, the membrane can be folded over the top of the gravel trench near the surface to prevent plugging of the trench during freezing conditions. Figure 11 shows a lined trench under construction. Liners are also used to protect structures on landfills. A simple technique which provides limited protection is to place an impervious membrane between the slab and subgrade with slab-on-grade construction. This type of barrier would be effective only for the life of the membrane and would require careful sealing of all underground utility lines where they pass through the membrane barrier.

[18] C. Wiegand, G. Gerdes, and B. Donahue, *Alternative for Upgrading or Closing Army Landfills Classified as Open Dumps*, Technical Report N-123/ADA113371 (CERL, 1982).

**Active Systems**

Active gas control systems can be divided into extraction and pressure systems. Both systems usually

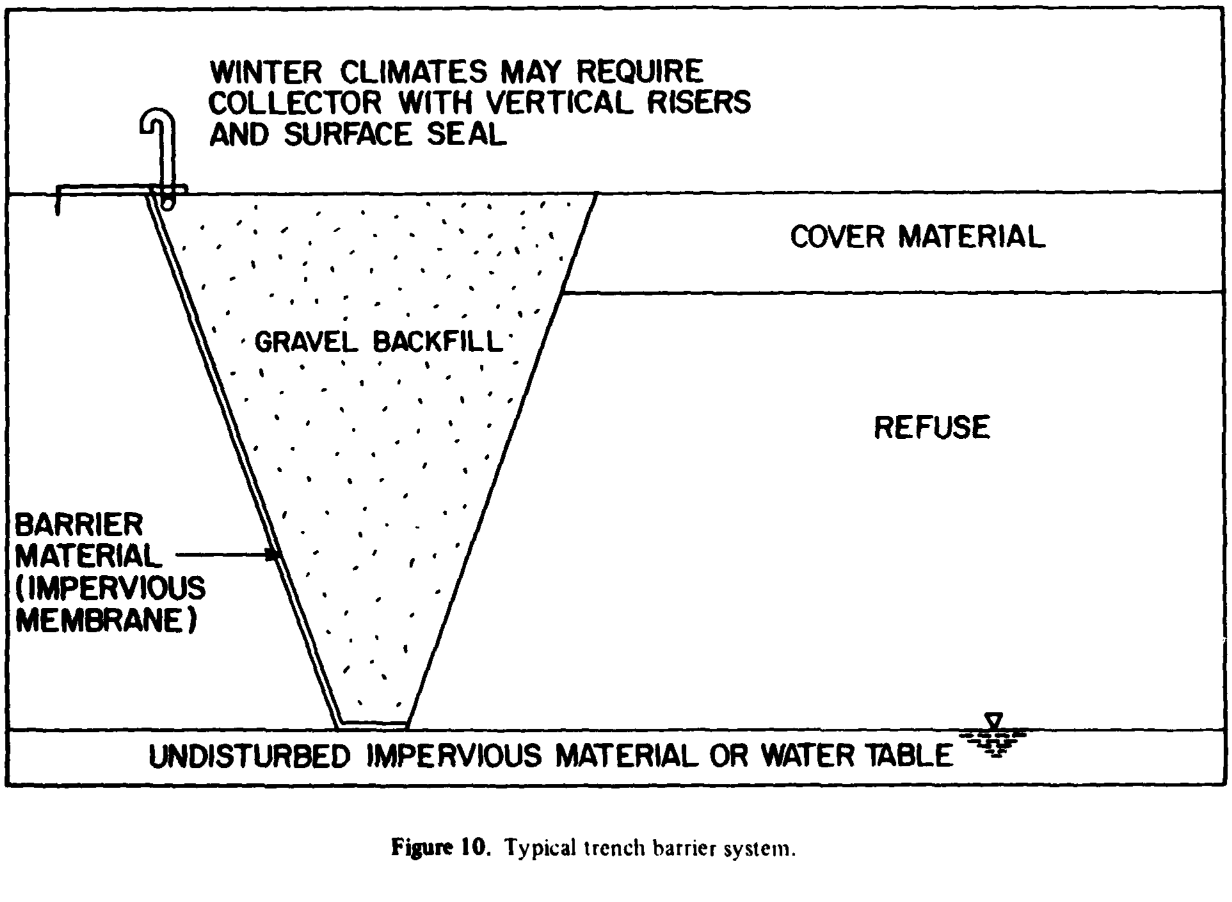


**Figure 10.** Typical trench barrier system.

**Figure 11.** Excavation for barrier/trench vent system at Lowell, MA, landfill.

incorporate some types of impermeable gas barrier system. Active extraction systems are considered the most efficient system to be installed in filled or older operating landfills. These systems usually incorporate a series of gas extraction wells installed within the perimeter of the landfill. If gas recovery is an objective, the wells can be systematically spread over the landfill itself. A landfill in Lycoming, PA, uses the wells shown in Figure 8. As the landfill was built up, additional concrete well sections and perforated PVC pipe were added and backfilled with gravel. In this way, the extraction wells acted as a passive venting system while the landfill was being built. When the landfill was complete, all the extraction wells would be manifolded to a common suction system for gas recovery. Figure 12 illustrates a typical extraction well.

The construction and materials for extraction wells are similar to those used for gas monitoring wells, only larger. The number of wells needed for any particular landfill is site-dependent. The density of the fill and surrounding soils, the depth of the refuse, and many other factors all affect the radius of influence of each extraction well. Quite often, when an extraction system is being developed for a closed landfill site, a pilot study of only a few wells will be installed first to determine the radius of influence in the area of the wells. Monitoring wells are used with velometers to determine how much negative pressure is developed in the adjacent monitoring probes as a result of exhausting the extraction wells. Provisions should be made in contracts for landfill extraction systems to allow for additional wells if the actual radius of influence is less than the design radius of influence.

A typical gas extraction control system would have wells placed along the perimeter of the landfill and located either internally or externally to the boundary of the refuse, depending on the site and situation. Spacing of the wells depends on the radius of influence and on proximity of structures that are to be protected. In some cases, up to a 160-ft (45-m) spacing has been used successfully. The extraction wells are constructed, using a 48-in. (1219-mm) auger to make a boring to the full depth of the landfill. In some cases, borings do not extend to the full depth of the landfill because of a high water table. A 4-in. (102-mm) PVC pipe which is perforated to within 5 to 10 ft (1.5 to 3 m) of the surface is generally installed in the boring. Coarse rock backfill is then placed around the slotted or perforated pipe in the boring. The upper 5 to 10 ft (1.5 to 3m) of the boring is sealed with bentonite and concrete to the surface to prevent air from being pulled into it. A header system incorporating gas valving and condensation traps connects all the wells to a suction system. The centrifugal blower creates a vacuum on the manifold to draw gas from the well system. The flow of gas in the soil and refuse is toward each well, and effectively controls any off-site gas migration. Depending on the location, the gas is either exhausted to the atmosphere, flared to prevent malodors, or recovered for on-site or near-site use. The

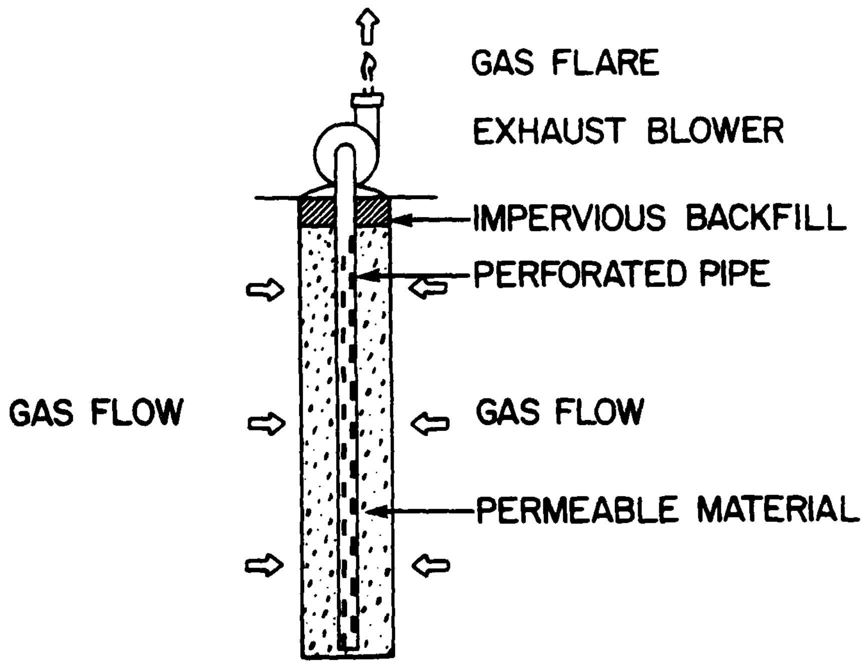


**Figure 12.** Gas extraction well for landfill gas control.

power extraction system to control gas migration is an accepted and widely used control strategy. When properly designed and installed, it is efficient and effective. Its cost is competitive with other systems; however, it requires more operation and maintenance than passive systems.

A pressure gas control system is sometimes considered when structures are being built or already exist on abandoned landfills. It is assumed that refuse all around and underneath the structure is generating gas and that the gas is collecting below the slab of the building. The system uses a blower to force air under the slab, developing a positive pressure to prevent gas from migrating toward the structure and exhausting any gas under the slab to the atmosphere. Care must be taken that all floor cracks and utility line entrances are sealed gas-tight; otherwise, air (and possibly gas) could actually be forced up into the building. Also, the porous layer or cavity underneath the slab must be continuous to allow for an unrestricted air flow under the entire slab. Quite often, a building will be constructed with footings under the structure that would prevent the entire subgrade under the slab from being effectively flushed of gas. Also, differential settlement under the slab might create void spaces that will aggravate pressure control problems by not allowing a uniform and complete air flow. Such systems will often incorporate a gas monitor with sensors under the slab that will trigger the blowers to come on at a low level and sound an alarm if gas concentrations continue to increase.

**Control System Selection**

The success or effectiveness of any control system must be continuously appraised until it can be proven that gas migration from the landfill is no longer a hazard. Probes or monitoring wells should be permanently

installed between the control system and the facilities to be protected. In structures built on landfills, subfloor probes should be monitored continuously or connected to an alarm system. These sensors will trigger an alarm circuit, switch on a ventilation system, or both.

Selection of a control system is site-specific and is based on several factors. Table 6 summarizes the descriptions, advantages, and disadvantages of various control strategies. The effectiveness of a control system over time is the most important selection factor. However, consideration should be given to how the system will operate under changing site and environmental conditions after it has been constructed. For example, the effect of sediment or ice clogging on granular trenches should be considered. In this case, the small additional cost of an impervious liner might be justified, although the impermeable barrier would probably provide an acceptable level of methane control even if the trench clogged.

The ability to detect and repair system failures is another important factor. Mechanical extraction or pressure systems would present less of a repair problem than a cracked membrane barrier buried under 10 ft (3 m) of gravel backfill. The downtime associated with system failures should also be considered, as should a control system's adaptability to modification. The ability to change a system to obtain maximum effectiveness with changing circumstances is considered as the system's flexibility. Active ventilation systems provide far more adaptability and flexibility than a passive trench system.

Environmental impacts and disturbance during construction should be considered when selecting a gas control system. The environmental impacts usually considered are malodor, noise, and aesthetics. A barrier trench is considered to be silent and relatively unobtrusive visually, but will possibly vent odoriferous gases. On the other hand, noise will be associated with the blowers of an active extraction well system, but the gases can be flared to prevent malodors. Extensive excavation and backfilling are required for constructing barrier trenches, but this disturbance is minimized with extraction wells. Safety precautions should be taken if any construction will be done inside a building on a landfill (e.g., drilling through the slab to install probes). Drilling could be hazardous if gas concentrations under the slab are unknown, so excavating the building during boring should be considered.

When evaluating both pressure and extraction systems, the problem of changing the rate and even the type of decomposition taking place in the landfill should be considered. Pumping air into the landfill will affect the anaerobic environment which produces methane. Also, underground fires are possible when large amounts of air are forced into a landfill which is already producing and storing methane. With an extraction system, the problem is easily solved by flaring or exhausting the gas above roof level to avoid bad odors. However, with pressure systems, the landfill gas and air mixture must be vented, and the odors could become a nuisance in a populated area.

#### Gas Recovery as a Control Strategy

In most cases, it would not be economical to recover and upgrade landfill gas; however, many factors must be considered on a site-by-site basis. The ultimate use of the gas is a very important factor when determining whether or not to recover it. If the gas is to be used on-site for engines requiring low-Btu gas, the economics involved could be considered justified. Also, the rising prices of natural gas and other energy sources will play a large role in the development of economical landfill gas recovery operations. A recovery and use study conducted at Mountain View, CA, determined the heating value of the raw landfill gas to be 4000 KC/m$^3$ as compared to 8900 KC/m$^3$ for natural gas. There was no system for on-site use. To inject the gas into the natural gas pipeline, it was decided that the heating value had to be brought up to 6225 KC/m$^3$. To reach this quality required using dehydration and carbon dioxide removal by the molecular sieve process. During the pilot-scale phase of the project, a landfill gas flow of 28,300 m$^3$/day was used. Table 7 shows the cost estimate for this gas recovery project. At a full-scale production rate of 141 500 m$^3$/day, lowered energy costs for pumping and upgrading the gas would reduce the cost about $8.00 per million KC. Although the initial costs are high for gas recovery and landfill gas economics indicate that energy costs will be higher than the current price of natural gas and oil, the technology is promising, since the economics are already competitive with synthetic natural gas or liquified natural gas.[19]

[19]S. C. James and C. W. Rhyne, *Methane Production, Recovery, and Utilization from Landfills* (USEPA).

Table 6
Gas Control Measures for Landfills
(From *Methane from Landfills: Hazards and Opportunities*, Symposium Proceedings, Denver, CO, March 21-23, 1979.)

| Control System | Description | Advantages | Disadvantages |
|---|---|---|---|
| Trench with granular backfill | Along all boundaries to completely enclose each site. Gravel backfill greater than 6.4 m. Depth: 6.1 m or to groundwater table or bedrock, whichever is less. | Low cost at depths up to 3.7 m. Little maintenance is required. The granular backfill provides a highly permeable region venting to the air to allow low-resistance passage of gas. | Costs escalate rapidly at depths greater than 6.1 m. The barrier may not be effective if pervious natural soil layers exist on the outside of the trench. Gas could migrate and/or diffuse across the barrier. Difficult to construct at depths greater than 9.1 m and impractical to construct at depths greater than 14 m. Not controllable. |
| Trench with impervious membrane | Along all boundaries to completely enclose each site. Impervious membrane. 30-mil thickness. Depth: to groundwater or unfissured bedrock. | Low costs at depths between 3.7 and 9.1 m. The membrane can provide a positive seal and be a barrier against gas and leachate. Little maintenance is required. Granular backfill on the landfill side of the membrane allows methane gas to vent to the air. | Costs become exceptionally high below a 9.1-m depth. The barrier may not be effective unless it extends into the groundwater table to eliminate gas migration beneath the membrane. Difficult to construct at depths greater than 9.1 m and impractical at depths greater than 14 m. Not controllable. |
| Low-flow and high-flow forced induction wells | Perimeter walls–space 30.5 m on center. Interior wells–space 61 m on centers. Burners can be used for odor control. Depth: 6.1 m or to groundwater or bedrock, whichever is less. | Very reliable and effective at controlling gas migration from landfills. Provides positive controlled removal of methane gas. Can be used as a barrier around the landfill perimeter by spacing close enough to provide overlapping negative pressures. | Relatively costly. Requires maintenance and periodic inspection. High-flow has greater power and maintenance cost than low-flow system. |
| Natural induction wells | Perimeter and interior spaced same as forced induction wells. Depth: same as above. | Can install at depths greater than 30.5 m. Can cover a large area. Negligible maintenance and comparatively low operating costs. | Localized venting of methane. Large number required to achieve control of migration. Is uneconomical. Reliability and effectiveness have been inadequate. Not controllable. |
| Natural induction wells with subsurface collector pipes | Perimeter and interior spaced same as forced induction wells. Depth: same as above. | Can install wells to depths greater than 30.5 m. Can install collector pipes at varying depths. Can cover a large area of landfill surface using interconnecting collectors between wells. Negligible maintenance and operating costs. | Extensive piping and well system is needed at high cost. Reliability and effectiveness may be unsatisfactory, since this system basically combines the trench and well systems. Not controllable. |

**Table 7**
**Cost Estimate for Landfill Gas Recovery at Mountain View, California**
**(From S. C. James and C. W. Rhyne, *Methane Production, Recovery, and Utilization from Landfills*, USEPA.)**

| | Equipment Cost | Installed Cost |
|---|---|---|
| Molecular sieves | $245,000 | $368,000 |
| Compression | 200,000 | 350,000 |
| Wells and gathering system | — | 70,000 |
| Total installed cost | | $788,000 |

| Yearly Costs | $/Year |
|---|---|
| Maintenance | 25,000 |
| Manpower | 30,000 |
| Fixed charges | 195,000 |
| Feedstock costs | 22,320 |
| Total | 272,320 |
| Energy output, MBTU/yr | 97,650 |
| Energy costs, $/MBTU | 2.79 |

# 6 GAS MIGRATION AND CONTROL MODELING

Computer simulations of the gas flow in and around landfills have been developed to predict the gas production rate and gas-flow permeability and to predict the effect of control devices on gas migration; however, only limited field data are available to verify these models. Computer programs have been developed that use site-specific input which will better predict the movement of methane from a landfill on a site-by-site basis.[20] However, since the conditions at each landfill site are different, designers should be cautioned in using computer simulations for design purposes.

### Gas Production and Flow Models

A study made for the New York State Department of Health used field measurements of the changes in landfill gas pressure caused by pumping gas out of the landfill to calculate the gas-production rate and the permeability of the landfill for gas flow. Four wells and 48 pressure probes were installed in a 16-hectare test section of the 1200-hectare Fresh Kills Landfill in Staten Island. The wells and pressure probes' measurement were used to calibrate the computer model whose results were then compared to those of flux box measurements performed on the same test section. The computer model predicted a gas-flow rate of 3.36 $m^3$/min/ha using three different withdrawal rates. During the same period (September-October 1978), flux box measurements measured the gas being vented from the landfill surface. Gas-production rates from these measurements were calculated to be 3.63 $m^3$/min/ha, in good agreement with the computer model. The conductance for the horizontal flow of gas was calculated to be 0.15 $cm^2/(s\ Pa)$, while the vertical conductance was calculated at 0.004 $cm^2/(s\ Pa)$, using the production rate and measured vertical pressure gradient. Thus, there is much less resistance to gas flow in the horizontal direction than in the vertical direction, a condition that is advantageous for using extraction wells to withdraw landfill gas. The lower conductance in the vertical direction will restrict the flow of air into the surface of the landfill, while allowing landfill gas to move horizontally to the extraction well. This example shows how a computer model could be used to estimate design values such as the radius of influence for a gas extraction system.[21]

[20] C. A. Moore, I. S. Rai, and J. Lynch, "Computer Design of Landfill Methane Migration Control," *JEED*, Vol 108, No. EE1 (ASCE, February 1982).

[21] An-Hua Lu and Charles Kunz, "Gas-Flow Model to Determine Methane Production at Sanitary Landfills," *Environmental Science and Technology*, Vol 15, No. 4 (April 1981).

Computer programs have been developed at Ohio State University for the U.S. Environmental Protection Agency which predict gas concentrations and migration from sanitary landfills. The methane migration problems have been modeled after combined transition-region multicomponent gas flow in porous media. The combined transition nature of gas flow refers to the tendency for methane to flow under both partial and total pressure gradients. The transition region refers to the tendency for methane to collide with both other gas molecules in soil pore spaces and with the soil particles themselves. The flow is multicomponent, because several other gases are involved, such as carbon dioxide and nitrogen.

Table 8 is a typical printout of input data used to describe a landfill situation. Input data consist of information delineating the landfill's geometry, soil type, decomposition history, and the gases involved. This model was verified based on limited field data for a landfill in Azusa, CA. The landfill consisted of a 0.3-hectare site in a gravel pit. Carbon dioxide concentrations were used to verify the model since they provided the most complete field data. Table 9

**Table 8**
**Typical Computer Input to a Gas Control Design Program**
**(From C. A. Moore, I. S. Rai, and A. A. Alzaydi, "Methane Migration Around Sanitary Landfills," *Journal of the Geotechnical Engineering Division [JGED]*, Vol 105, No. GT2 [ASCE, February 1979], pp 131-144.)**

| | | |
|---|---|---|
| NUMBER OF MESH POINTS UP TO END OF FILL | = | 21 |
| NUMBER OF MESH POINTS UP TO DEPTH OF FILL | = | 3 |
| NUMBER OF MESH POINTS UP TO END OF LAND | = | 51 |
| NUMBER OF MESH POINTS UP TO DEPTH OF LAND | = | 5 |
| NUMBER OF MESH POINTS UP TO VENT | = | 20 |
| NUMBER OF MESH POINTS UP TO DEPTH OF VENT | = | 1 |
| SPATIAL MESH SIZE (CM) | = | 800.000 |
| NUMBER OF STEPS BETWEEN PRINTOUTS | = | 100 |
| MAXIMUM NUMBER OF STEPS ALLOWED | = | 2000 |
| INITIAL DTAU (DAYS) | = | 1.0 |
| MAXIMUM TIME ALLOWED (DAYS) | = | 730000.0 |
| MAXIMUM DTAU (DAYS) = 1.2*OX*DX/DIJ (MAX) | = | 303.0 |
| POROSITY OF SOILS (DIMENSIONLESS) | = | 0.400 |
| TORTUOSITY (DIMENSIONLESS) | = | 2.250 |
| SURFACE PERMEABILITY COEFFICIENT | = | 0.398D-04 |
| END PERMEABILITY COEFFICIENT | = | 0.0 |
| PERMEABILITY COEFFICIENT FOR THE VENT | = | 0.398D-04 |
| PERMEABILITY MULTIPLIER FOR THE VENT | = | 0.100D+01 |
| INITIAL HARDNESS | = | 75.000 |
| INITIAL PH VALUE | = | 6.500 |
| DEGREE OF SATURATION | = | 40.000 |
| MOLECULAR WEIGHT OF GAS B (GM/MOLE) | = | 28.800 |
| MOLECULAR WEIGHT OF GAS A (GM/MOLE) | = | 16.050 |
| PRESSURE (ATMOS) | = | 1.000 |
| TEMPERATURE (DEG KELVIN) | = | 298.000 |
| BULK DIFFUSION COEFFICIENT (CM SQ AT MOS/SEC) | = | 0.226 |
| INITIAL MOLE FRACTION IN FILL | = | 0.700 |
| TERMINATION MOLE FRACTION | = | 0.050 |
| DECOMPOSITION TIME (DAYS) | = | 1825.000 |

| NUMBER | PORE RADIUS | VOLUMETRIC FRACTION |
|---|---|---|
| 1 | 400000.00 | 0.4000 |

HISTORY OF FILL CONCENTRATIONS

| TIME (DAYS) | MOLE FRACTION |
|---|---|
| 0.0 | 0.70 |
| 1825.00 | 0.70 |

AXISYMMETRIC FLOW PROGRAM
CHEMICAL REACTION NOT CONSIDERED

compares the measured carbon dioxide measurements over a 3-year period with those predicted by the computer model.[22]

**Gas Migration and Control Models**

Several computer models have been developed to predict the extent of landfill gas migration and the effects of various control techniques on migration. One such model, developed at the University of Waterloo, was calibrated by monitoring gas compositions and pressures before, during, and after application of a zone of negative pressure within the landfill. A field study was done to evaluate the effectiveness of a trench in controlling off-site gas migration and the results compared to the computer model predictions. Although the comparison between actual and predicted results is only fair, it must be noted that measured concentrations were highly variable. The measured field concentrations indicate that the vent trench, as installed, is ineffective in controlling off-site migration -the same conclusion predicted by the computer model. Thus, the use of the computer model as a decision tool for design appears justified.[23]

Research at Ohio State University has developed computer models that simulate various control systems for gas migration on an example typical landfill. These models should allow economical evaluation of alternative designs to select the optimum system. The models should also allow the designer to determine what aspects most influence a system's effectiveness so that they can be controlled carefully during installation. Finally, if an installed system is determined to be ineffective, the computer model can be used to develop modifications to remedy the problem. In this model, the landfill was circular and had a 160-m radius. The landfill was 16 m deep with impervious bedrock or a groundwater table at a depth of 32 m. The effects of natural, forced recharge and of forced exhaust venting systems were compared to no control and perfect methane removal. The unforced trench was effective. The forced exhaust trench was also effective; however, shutdown of the exhaust system could result in relatively rapid increases in methane concentration beyond the trench. The forced recharge system was the most effective system studied and did not pose as great a threat of methane buildup after the system shutdown as did the forced exhaust. Computer costs on an IBM 370/168 were between \$25 to \$2000 per model run, depending on the complexity of the situation; the cost of runs for many practical design problems is about \$100 each.[24]

**Limitations of Modeling Systems**

It is very hard to characterize the physical, chemical, and biological conditions in and around a landfill. This

[22]C. A. Moore, I. S. Rai, and A. A. Alzaydi, "Methane Migration Around Sanitary Landfills," *Journal of the Geotechnical Engineering Division (JGED)*, Vol 105, No. GT2 (ASCE, February 1979), pp 131-144.

[23]T. W. Constable, G. J. Farquhar, and B. N. Clement, *Gas Migration Modeling* (University of Waterloo, Waterloo, Ontario).

[24]C. A. Moore and I. S. Rai, "Design Criteria for Gas Migration in Control Devices," *Management of Gas and Leachate in Landfills: Proceedings of 3rd Annual Municipal Solid Waste Research Symposium*, EPA-600/9-77-026 (USEPA, 1977).

**Table 9**
**Comparison of Measured and Predicted Carbon Dioxide Concentrations at the Azusa, California, Landfill**
**(From C. A. Moore, I. S. Rai, and A. A. Alzaydi, "Methane Migration Around Sanitary Landfills," *Journal of the Geotechnical Engineering Division [JGED]*, Vol 105, No. GT2 [ASCE, February 1979], pp 131-144.)**

| Quantity | Depth, in Meters | 1 | 2 | 3 |
|---|---|---|---|---|
| Mean observed concentration | 13.8 | 12.5 | 12.0 | 15.5 |
| | 24.6 | 9.0 | 7.0 | |
| | 36.8 | 2.0 | 7.0 | 8.0 |
| Predicted concentration | 13.8 | 12.7 | 13.5 | 13.2 |
| | 24.6 | 5.9 | 8.4 | 9.2 |
| | 36.8 | 0.6 | 2.4 | 3.7 |

makes describing and predicting the internal environment of a landfill very costly and difficult. Table 10 summarizes some of the data needed to simulate the changes in gas composition and pressure as a function of depth.[25] These values have been gathered from several different sources and are representative of a typical landfill. As shown by this table, the task of characterizing a specific landfill would be difficult, and many factors, such as differential settlement, would be unknown. The use of computer models to simulate new landfills and predict the effects of migration control systems can be very helpful. If predictive models are used from the beginning of a landfill design and construction, as many unknowns as possible can be uncovered and used in the computer model. The designer should be cautioned against interpreting model conclusions too broadly. Like the landfills themselves, the models are unique. However, they often involve the use of numerous simplifying assumptions, such as homogeneous material involved in gas transmission, a point source, or a near point source for gas generation.

The information required to model closed or abandoned landfills is usually very hard to obtain. However, the computer model is still a very useful

[25] A. N. Findikakis and J. O. Leckie, "Numerical Simulation of Gas Flow in Sanitary Landfills," *JEED*, Vol 105, No. EE5 (ASCE, October 1979), pp 927-940.

**Table 10**
**Physical and Chemical Parameters Used in Typical Numerical Simulation Examples**
**(From A. N. Findikakis and J. O. Leckie, "Numerical Simulation of Gas Flow in Sanitary Landfills," *JEED*, Vol 105, No. EE5 [ASCE, October 1979], pp 927-940.)**

| Landfill Data | Sanitary Landfill Number 1* | Sanitary Landfill Number 2** |
|---|---|---|
| Landfill depth, in meters | 27.7 | 33 |
| Cover thickness, in meters | 2.0 | 1.0 |
| Refuse permeability, in Darcys | 1.0 | 1.0 |
| Refuse porosity | 0.5 | 0.5 |
| Refuse density, in $kg/m^3$ | 815 | 700 |
| Moisture content, as a percentage of wet weight | 19 | 30 |
| Refuse composition,$^+$ as a percentage: | | |
| Readily degradable | 15 | 15 |
| Moderately degradable | 55 | 55 |
| Slowly degradable | 30 | 30 |
| Refuse composition, $_{+1/2}$, in years: | | |
| Readily degradable | 5 | 0.5 |
| Moderately degradable | 30 | 3.5 |
| Slowly degradable | 40 | 25 |
| Gas-generation potential$^+$: | | |
| $CH_4$, in cu ft/lb of refuse | 1.0 | 1.0 |
| ($kg/m^3$) | (0.06) | (0.06) |
| $CO_2$, in cu ft/lb of refuse | 1.0 | 1.0 |
| ($kg/m^3$) | (0.06) | (0.06) |
| Cover permeability, in Darcys | 0.1 | 0.1 |
| Cover porosity | 0.5 | 0.75 |
| Ambient temperature, in degrees Celsius | 17.8 | 18.6 |
| Cover temperature, in degrees Celsius | 29.2 | 20.0 |
| Temperature gradient in fill, in degrees Celsius per meter | 0.4 | 0.5 |

*Except where otherwise noted, all data provided by City of Glendale; assumed eight layers of refuse placed at equal time intervals over 15 years.
**Except where otherwise noted, all data provided by Reserve Synthetic Fuels, Inc.; assumed eight layers of refuse placed at equal intervals over 15 years.
+Estimated from average refuse composition and stoichiometry of anaerobic biodegradation of organics.

tool in designing and optimizing control systems at landfill sites. In any system, regardless of its design and construction, the effectiveness can only be proven by a comprehensive gas monitoring system which lasts as long as there is evidence of gas in or around the landfill.

# 7 EXAMPLES OF GAS CONTROL APPLICATIONS

**Richmond, VA, Landfill Gas Control**

In 1975, an interior explosion blew doors and windows out of an apartment building in Richmond, VA. Fire department personnel detected combustible gas in the first floor walls and exterior weepholes. Since the city-operated Fells Street Landfill was close to the building, it was investigated as a potential source of the explosive gas. Test borings indicated gas concentrations well in excess of the lower explosive limit. The city also found another landfill (the Whitcomb Street Landfill) that presented a potential hazard. The Fells Street Landfill covers 16 hectares with refuse buried to a depth of 24 m, while the Whitcomb Street Landfill covers 6 hectares with refuse to a depth of 12 m. Both landfills border developed land and have city schools located adjacent to or on them. Since the landfill gas problem exceeded the expertise of the city personnel, the EPA was asked to provide a list of consultants with landfill gas experience. A contractor was then hired to sample gas around the landfills at different depths; the results were used to develop contours showing the trend of methane migration around the landfills. The following recommendations were then made to the city:

1. Affected residences and businesses should be advised of the potential hazard and asked to keep buildings well-ventilated.

2. Continuous, automatic methane detection and alarm systems should be installed in the school buildings.

3. All applicants for building permits in the affected areas should be required to demonstrate that either (a) no methane problem exists on the prospective site or (b) protective features will be included in the building design.

4. The city should begin a two-phase program to eliminate the movement of methane outside of the landfills. The first phase should be the construction of small-scale "pilot" systems, the second phase would be construction of a full-scale landfill gas control system.

Fire inspectors informed residents about the problem by distributing notices outlining precautions to be taken and providing an emergency telephone number. Care must be exercised when informing the public of landfill gas problems. Information that is too technical for the general public to interpret can be confusing and might cause unnecessary fear and a negative reaction. Tables 11 and 12 provide examples of appropriate written communication.

The city installed continuous monitoring systems in the school buildings. Sensors were installed in nearly every room, and a central control panel was placed in the building with a remote link to the school board's radio room for night and weekend monitoring. A visual alarm was set at 5 percent LEL with an audible alarm at 10 percent LEL. The Building Commissioner's Office now requires applicants for building permits in sites in the "zero" gas contour to hire a certified professional engineer to determine if a methane problem exists. If concentrations are greater than 2 percent LEL, three features must be included in the building's design:

1. Adequate ventilation

2. Automatic methane detection devices

3. Sealing of the ground level on basement floors.

Two pilot control systems were constructed at the schools to evaluate the performance of a gas collection control system and to provide early protection of the buildings. Performance data from the pilot system was then used to design the full-scale control systems. The control systems include gas extraction wells, gas collection headers, vacuum blowers, and waste gas burners. The extraction wells were drilled with a 76-cm auger to groundwater or natural ground below the fill. Perforated PVC pipe was installed in the boring which was then backfilled with large ballast stone. Solid PVC pipe was used on the upper 3 m of the well which was backfilled with compacted soil. Polyethylene pipe was used for the headers because of its flexibility and chemical resistance. Condensation traps were installed at low points in the headers which were connected to each well with branch tees and individual control valves. Centrifugal blowers were installed to

**Table 11**
**Example of Written Communication After Landfill Gas Incident**
**(From *Methane From Landfills: Hazards and Opportunities*, Symposium Proceedings, Denver, CO, March 21-23, 1979.)**

Dear Resident:

According to information furnished by an independent consulting firm, there appears to be reasonable evidence of concentrations of methane gas in an area of approximately (state area).

Therefore, you are advised to take the following precautions:

1. All basements and/or crawl spaces should be opened for natural ventilation.

2. Any unusual odors should be reported immediately to (emergency number).

3. All living areas should be ventilated. This means that windows should be left open and closet doors should also be left open.

Concentrations of methane gas are not usually dangerous in a well-vented area, according to the independent consultant. Therefore, it is most important that your home or apartment be kept well ventilated at all times.

Your cooperation is sincerely appreciated.

Signature Block

**Table 12**
**Example of Written Communication After Landfill Gas Incident**
**(From *Methane From Landfills: Hazards and Opportunities*, Symposium Proceedings, Denver, CO, March 21-23, 1979.)**

Dear Resident:

As you are aware, notices were distributed to your neighborhood in (date) advising residents to take precautions against the possible accumulation of methane gas. Although we know of no change in the general migration of methane gas in the area, this is to remind you that the need for ventilation is even greater during cold weather. Accordingly, you are again advised to take the following precautions:

1. All basement and crawl spaces should be opened for natural ventilation.

2. All living areas should be ventilated. Where forced air ventilation is not provided, our consultant's staff advises that windows should be opened at least one inch, preferably from the top. Storm windows should also be opened at least one inch. Closet doors should be left open as well.

3. Should you have any questions concerning methane gas in your building or should you note any unusual odors, please call (emergency number) immediately.

Concentrations of methane gas may be odorless and are not usually dangerous in a well-vented area. According to the independent consultant, it is most important that your home, apartment, dwelling, or other structure be kept well ventilated at all times.

As a step to alleviate the problem, (appropriate authority) has authorized initial steps for the establishment of a gas control system. In the meantime, we sincerely appreciate your cooperation in following the above safety precautions.

Signature Block

draw the gas from the wells through the header system to flares, which burn the landfill gas to prevent malodors.

Subsurface negative pressures were measured to determine the radius of influence for the extraction wells. The optimum well spacing for the sites was determined to be 61 m; this figure was then used to design the full-scale control systems. Provisions were made to install additional wells if gaps were found in the extraction system. When the full-scale system is built, gas probes will be re-established to assess the effectiveness of the control systems.[26]

**Fort Belvoir, VA, Gas Control**

A review of aerial photographs by the Facility Engineer's office at Fort Belvoir indicated the possibility of a landfill in the vicinity of Markham Elementary School on post. A "walkover" of the site revealed that differential settlement all around the school had resulted in cracked sidewalks, cracked paved playground areas, and one long crack along the foundation. Shallow borings were made with a hand auger near the foundation of the building and readings made with a portable combustible gas meter. Concentrations of methane as high as 40 percent were found near the building. A study was then begun to determine:

1. The concentration of gas in the soils adjacent to the school and around housing areas near the landfill

2. The actual boundary of the landfill

3. The local groundwater table

4. Whether permanent gas monitoring wells had been installed between the landfill and housing areas.

A drilling program was then conducted along the suspected borders of the landfill. As borings were made, soil classifications and the depth to refuse and water table were logged. Gas measurements were made and recorded after the auger had been removed from the boring. This information was used to lay out the actual boundary of the landfill (see Figures 13 and 14). Monitoring wells were installed between the landfill boundary and the housing areas to determine if there was any off-site gas migration. Borings were also made around the foundation of the school to determine how much of the building was built on refuse. Gas monitoring was conducted in crawl spaces under the housing units in George Washington Village and in the ductwork which was laid under the slabs at the housing area, Dogue Creek Village, next to the school. Fire department personnel conducted combustible gas surveys in the school periodically until a continuous monitoring system was installed. The results of the drilling program and gas surveys were:

1. Borings showed that the west half of the north wing and the north side of the east wing of Markham School were directly over about 3 m of refuse.

2. Gas readings as high as 28 percent methane were obtained from borings along the west side of the north wing. About 20 borings made in this area showed evidence of refuse and methane.

3. Gas monitoring wells installed between the landfill and Dogue Creek Village showed gas migrating from the landfill toward the housing units. The boring and well installed just 30 m from the closest housing unit had an initial methane concentration of 54 percent.

4. Gas monitoring wells installed between George Washington Village and the landfill area on the east site of Mount Vernon Road showed relatively high gas readings. This suggested that gas was migrating from the landfill under the road toward the housing units.

5. Sandy, gravelly units in the underlying Potomac Group provided pathways for the movement of gas away from the fill.

6. There was evidence of a local perched water table in the landfills. Water levels from the well drilled near Markham School suggested that the regional water table was about 9 m below ground surface.

Three alternatives for gas control were considered as a result of the investigation:

1. Excavation and removal of the immediate gas source (the refuse)

2. Construction of an impermeable barrier trench along the landfill perimeter to prevent the movement of gas into surrounding structures, and removal of the refuse from beneath the school

3. Installation of an active venting system using extraction wells.

[26] D. O. Nutall, "Control of Gas Migration in Urban Landfills," *Public Works* (July 1980), pp 46-49.

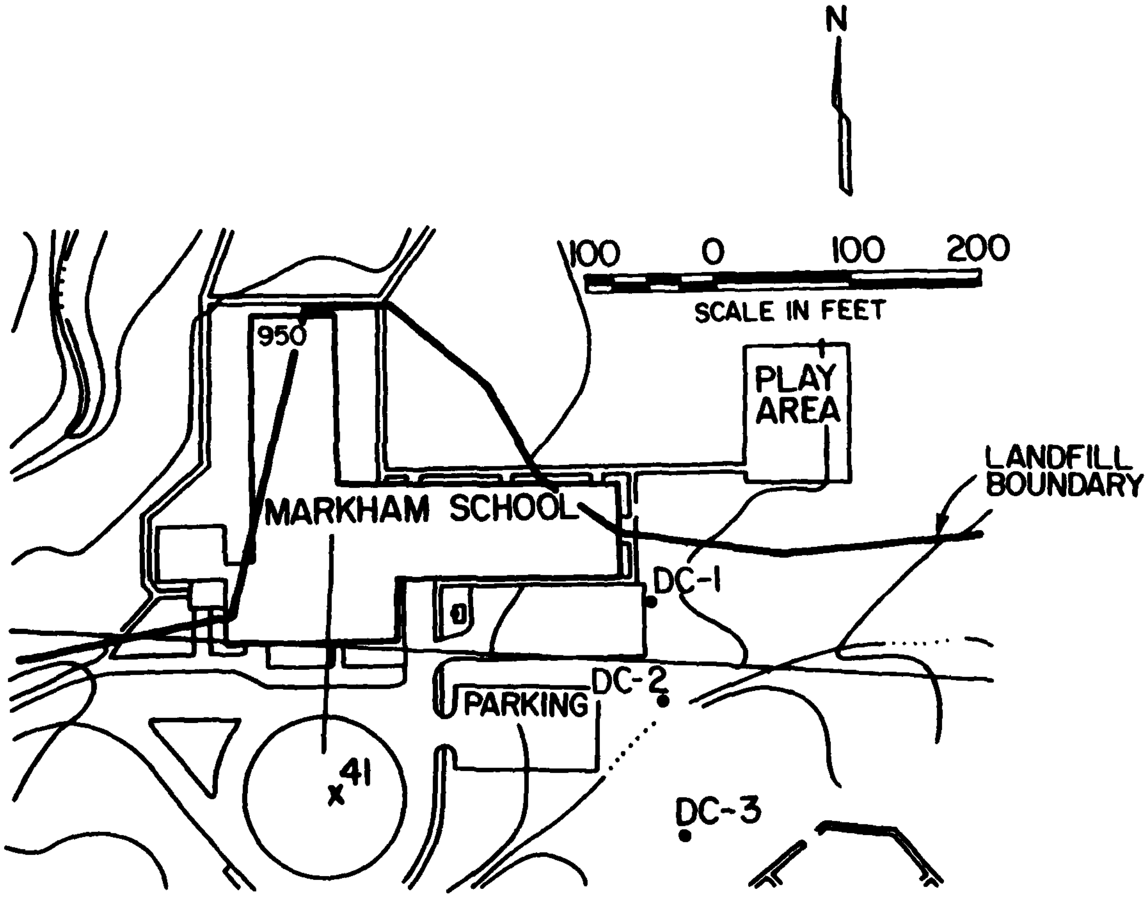


**Figure 13.** Location of the gas-monitoring wells and the landfill boundary at Markham School, Fort Belvoir, VA. (From R. A. Shafer, P. G. Malone, and J. E. Lee, *Investigation of Landfill Gas Migration Near Markham School and George Washington Village, Fort Belvoir, VA* [August 1980].)

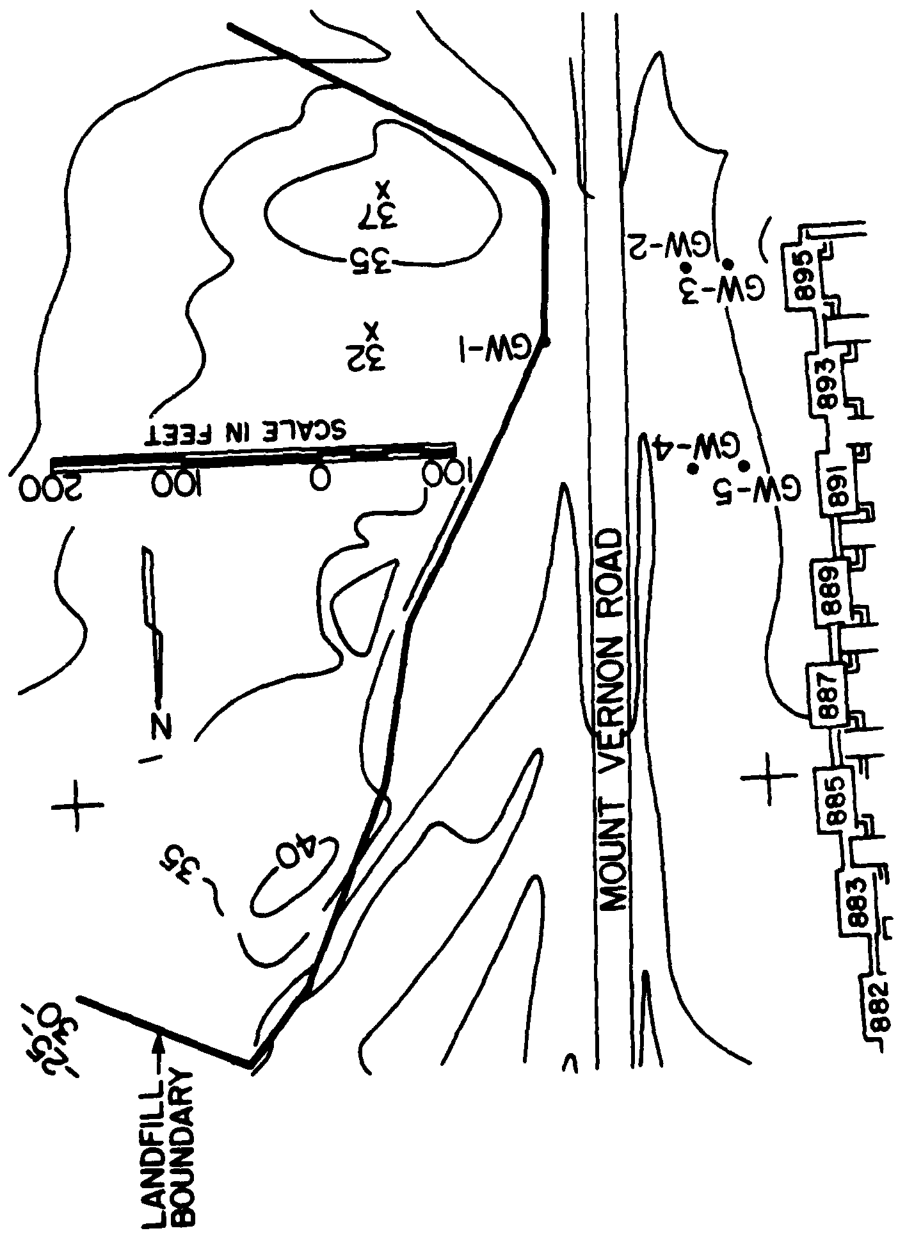


**Figure 14.** Location of gas-monitoring wells and landfill boundary at the George Washington Village landfill site, Fort Belvoir, VA (August 1980) (Reference 7).

Many advantages and disadvantages are associated with each control system. The advantage of excavating and hauling off the refuse is removal of the source of gas. The disadvantages include:

1. The nearest permitted landfill (Cullum Woods Fill) that could be expanded to accept the refuse is about 5.3 km by road from the Markham School and George Washington Village sites.

2. The borders of the refuse would have to be moved at least 180 m from its present boundary to insure that a reasonable buffer area was established between the housing units and the methane source.

3. The entire thickness of refuse would have to be excavated; also, any obvious sand or gravel units under the refuse would have to be removed, interrupted by barriers, or vented.

4. The foundation under Markham School would have to be braced so that refuse could be excavated from under it.

Table 13 provides estimates for the costs for removing the refuse.

The advantage of a barrier trench system, as for any passive control system, is low operation and maintenance costs. The disadvantages include:

1. Dependence on the saturated zone to form the bottom of the barrier system

2. The requirement that the barrier vent system extend under the eastern and northern wings of the school building and that refuse below the foundation be removed and replaced with clean fill.

The operation of removing the refuse from beneath the school would be very complicated and costly. Table 14 gives a preliminary cost estimate for constructing the barrier trench.

In this example, using a gas extraction system would have three advantages:

1. There is no requirement for removal or reburial of refuse.

**Table 13**
**Preliminary Cost Estimate for Excavation and Reburial of Refuse**
**(From R. A. Shafer, P. G. Malone, and J. E. Lee, *Investigation of Landfill Gas Migration Near Markham School and George Washington Village*, Fort Belvoir, VA, August 1980.)**

| | | |
|---|---|---|
| Buffer Zone Width = 600 ft | | |
| A. Amount of refuse to be removed. | | |
| West side of George Washington landfill site = | 78,000 cu yd | |
| South side of Markham School = | 163,000 cu yd | |
| 241,000 cu yd @ 900 lb/cu yd = | 108,450 tons | |
| Costs to excavate = | | $2,169,000 |
| Material hauling $0.22/ton-mile | | |
| 3.3 miles distance for 108,450 tons = | | 78,700 |
| Bracing of building foundation (est.) at Markham School = | | 40,000 |
| B. *Refilling of excavation* | | |
| Borrow excavation (clean dirt) = $4.00/cu yd | | |
| 241,000 cu yd @ $4.00/cu yd = | | 964,000 |
| Material hauling $0.22/ton-mile = | | |
| 100 lb/cu ft = 1.35 tons/cu yd | | |
| 32,500 tons 3.3 miles x $0.22 = | | 23,600 |
| | TOTAL | $3,275,300 |

**Table 14**
**Preliminary Cost Estimate for Barrier/Vent Structure (Virginia)**
**(From R. A. Shafer, P. G. Malone, and J. E. Lee, *Investigation of Landfill Gas Migration Near Markham School and George Washington Village, Fort Belvoir, VA*, August 1980.)**

| | |
|---|---|
| Length of Mount Vernon Section = 1175 lin ft | |
| Length of Markham School Section = 950 lin ft | |
| Excavation to remove refuse in area and immediately adjacent to school: | |
| Classified excavation solid waste = $9.00/cu yd | |
| 9100 cu yd x $9.00 = | $ 81,900 |
| 9100 cu yd x 900 lb/cu yd = 4059 tons | |
| Material hauling $0.22/ton-mile: | |
| 3.3 miles x 4095 tons x $0.22 = | 3,000 |
| Bracing of foundation at Markham School = | 40,000 |
| Borrow excavation (clean dirt) = $4.00/cu yd + trenched material | |
| 4400 x $4.00 = | 17,600 |
| Material hauling $0.22/ton mile | |
| 100 lb/cu ft = 2700 lb/cu yd = 1.35 tons/cu yd | |
| 4400 cu yd x 1.35 tons/cu yd = 5940 tons | |
| 5940 x 3.3 x $0.22 = | 4,300 |
| Trench excavation $18/cu yd | |
| 3 ft wide x 20 ft deep x 2125 ft = 1,275,000 cu ft | |
| 4722 cu yd excavated @ $18/cu yd = | 85,000 |
| 20-mil PVC membrane @ $0.60/sq ft | |
| 2125 ft x 20 ft = 42,500 sq ft | |
| Cost of membrane = | 25,500 |
| Gravel to backfill = 4722 cu yd | |
| $5.00/cu yd delivered = | 23,600 |
| TOTAL | $290,900 |

2. The system will remain operational, regardless of fluctuations in the water table.

3. Vacuum measuring equipment and gas detectors can be used on monitoring wells to demonstrate the effectiveness of the pumping in creating a gas flow gradient and in removing gas from the soil around the landfill.

The disadvantages associated with this system are:

1. Power is required to operate the pumping system.

2. The system requires maintenance and some minimum commitment of personnel for operation.

3. The system may have to be operated periodically as long as dangerous concentrations of gas are present.

Table 15 gives a cost estimate for the gas extraction system. The costs involved in constructing, operating, and maintaining each system, along with the initial considerations of the site geology and the boundary of the landfill, indicate that an active (pumped) gas collection system should be considered as a possible remedial measure. Refuse removal would be prohibitively expensive, and barrier systems alone might not be effective at this site.

# 8 POINTS OF CONTACT FOR OBTAINING ASSISTANCE

Several DA laboratories/agencies can help the FE and MACOM choose and set up various types of leachate control systems. Points of contact and brief descriptions of services provided follow.

Table 15
**Preliminary Cost Estimate for Pumped Gas Collection**
**(From R. A. Shafer, P. G. Malone, and J. E. Lee, *Investigation of Landfill Gas Migration Near Markham School and George Washington Village, Fort Belvoir, VA*, August 1980.)**

| | |
|---|---|
| Gas Extraction Wells | |
| Seventeen 36-in., gravel-packed borings with 4-in. PVC slotted casing; estimated depth each well = 10 ft | $ 34,000 |
| (Installation of well included fabrication of moisture traps and throttle valve systems.) | |
| Header Pipe | |
| 3000 ft of 14-in. polyethylene pipe, $22/lin ft | 66,000 |
| Trenching to depth of 3-ft (2-ft width) and burial of header pipe - $9/cu yd, for 667 cu yd | 6,000 |
| Gas Suction and Safety Equipment | |
| 3 - Rotary suction pumps with 7.5-hp motors $2000 each | 6,000 |
| Concrete pad for gas pump station (30 ft x 30 ft x 1 ft) $150/cu yd | 5,000 |
| Gas combustion flare with auto ignition system | 20,000 |
| Valving | 17,000 |
| Fencing | 2,000 |
| TOTAL | $156,000 |

**U.S. Army Construction Engineering Research Laboratory (CERL)**

Since 1978, CERL has been involved in a research project, in cooperation with the Waterways Experiment Station (WES), to evaluate the technical and economic aspects of sanitary landfill leachate and gas control at military installations using preventive and remedial measures. CERL is also tasked with developing and pilot testing selected short-range and long-term methods for controlling and treating leachate from abandoned and operating sanitary landfills. Reports will be prepared providing guidance to MACOMs, Districts, and FE personnel. CERL has also begun a "Small Problems Program" through which DA personnel can ask for 16 hours of free assistance to help identify or solve DA-related leachate or gas problems. A related report is also available: Technical Report N-78/ADA073894, *Simplified Sanitary Landfill Design*, August 1979, by G. L. Gerdes and B. A. Donahue.

For more information, contact CERL, P.O. Box 4005, Champaign, IL 61820; phone 217-352-6511, or Autovon through Chanute AFB. Point of contact is Dr. Edgar Smith, team leader of the Water Quality Management Team.

**U.S. Army Environmental Hygiene Agency (AEHA)**

The Solid Waste Branch, AEHA, helps Department of Defense installations evaluate existing and proposed solid waste management programs. This assistance includes two major services: (1) on-site evaluation of present sanitary landfill operational techniques and (2) hydrogeologic and soils analysis for recommending new sanitary landfill sites, as required for obtaining a State sanitary landfill permit. In addition, AEHA will locate and/or install monitoring wells up to a 120-ft (36-m) depth to determine groundwater contamination (i.e., leachate). Soil samples are analyzed at Aberdeen Proving Ground, MD, for permeabilities, densities, soil classification according to the Unified Soil Classification System, specific gravity, and cation exchange capacity, etc.

These services can be requested by the installation MACOM through the Commander, U.S. Army Health Services Command, ATTN: HSPA-P, Fort Sam Houston, TX 78234, with an information copy to Commander, U.S. Army Environmental Hygiene Agency, ATTN: HSE-ES, Aberdeen Proving Ground, MD 21010. The Commander, U.S. Army Health Services Command, will endorse the request with recommended action

to the AEHA, which will program requests, by priority, by fiscal year and quarter. All written requests should include an installation point of contact and telephone number.

Telephone consultation can be obtained by contacting Chief, Solid Waste Branch, Autovon 584-4211 (Commercial 301-671-4211); or Chief, Waste Disposal Engineering Division, Autovon 584-2024 (Commercial 301-671-2024).

**U.S. Army Waterways Experiment Station (WES)**

WES has been involved in several research projects to evaluate problems associated with the generation of leachate and gas in landfills. In cooperation with the EPA, WES has examined the leachate from mixed hazardous industrial and municipal wastes and conducted extensive field investigation on power generation wastes, municipal landfills, and industrial waste landfills. WES has also conducted field gas surveys and established three gas and leachate monitoring systems at Fort Belvoir, VA. In cooperation with CERL, WES is setting up two pilot-scale leachate treatment systems. WES is also doing a design study for a gas control system for a closed landfill.

WES has an extensive information base on landfill design, leachate and gas control, and hazardous waste disposal. More than 30 publications on municipal and hazardous waste disposal technology have been generated from the EPA and Army-sponsored research efforts at WES.

Point of Contact: Dr. Phillip G. Malone, P.O. Box 631, Vicksburg, MS 39180, Commercial: 601-634-3960; FTS: 542-3960.

**U.S. Army Toxic and Hazardous Materials Agency (USATHAMA)**

USATHAMA conducts installation assessments to search for, identify, and assess actual or potential chemical, biological, or radiological contamination and/or migration by reviewing records and interviewing present and former employees. The agency also conducts installation environmental contamination surveys to establish contamination levels and verifies whether there is migration by determining subsurface water movement patterns.

USATHAMA is the lead DOD agency for developing pollution abatement/containment technology for migrating contaminants and for contamination problems on excess properties. The agency also has design and process engineering expertise in these areas.

USATHAMA has developed a data management system for environmental contamination at assigned Army installations. Computer mapping of sampling points, groundwater head, chemical concentration contours, and borelog profiles are provided by interactive programs. In addition to the reduction of raw data, USATHAMA can provide bibliographic searching of open literature databases. Chemical and physical properties of compounds can be retrieved through telecommunication links with the National Institute of Health and with the Environmental Protection Agency. The agency maintains a registry of contamination from past operations at a summary level for each assigned Army installation.

Point of Contact: John K. Bartel, Aberdeen Proving Ground, MD 21010, DRXTH-TE, Commercial: 301-671-2466; Autovon: 584-2466.

# 9 SUMMARY

This report has provided information useful to Army personnel responsible for recognizing and solving potential problems from gas generated by landfills. This information will help these personnel recognize potential landfill gas problems, gauge their magnitude, and be aware of the installation's legal responsibilities.

This report has also provided information on selecting appropriate gas-monitoring control strategies, procedures and equipment and on the use of computer modeling to predict gas production and migration and the success of gas control devices.

Safety is a significant concern associated with landfill gas problems. The following special precautions are emphasized:

1. A worst case should be assumed; i.e., even though no adverse effects from a landfill have been observed in the past, one should not assume that there will be none in the future.

2. Strict safety rules should be followed when investigating suspected gas problems. "No-smoking" rules must be enforced, combustible gas detectors

should be kept in good working order, and the possibility of landfill gas producing an oxygen-deficient atmosphere should be of concern.

3. Consultant and construction firms used to assess or fix a hazardous landfill gas condition should be experienced, should understand the complexities involved with construction on landfills and controlling gas migration, and should be required to accept professional services liability.

4. Gas migration at landfills can be controlled in numerous ways, so deciding on the appropriate system will have to be done on a site-specific basis; however, the overriding concern in system selection should be safety.

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